

## **Instream flow studies on Muddy Creek, tributary to the Clarks Fork River**

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### **Abstract**

Muddy Creek has been identified as crucial habitat for a core conservation population of Yellowstone cutthroat trout (YCT; *Oncorhynchus clarki bouvieri*), an important game fish and species of greatest conservation need in Wyoming. Though YCT were historically widespread throughout the Clarks Fork drainage, only a few conservation populations remain. To help ensure the persistence of this population, the WGFD has selected the stream for instream flow water rights filing consideration. Securing an instream flow water right in Muddy Creek will help ensure that YCT remain in the creek by protecting existing base flow conditions against potential future consumptive water demands.

An instream flow investigation was conducted on Muddy Creek in 2014 and the resulting flow recommendations are reported here. One stream segment was selected for the study, which was chosen considering land ownership, hydrology, and stream channel characteristics to maintain or improve the important YCT population. Several modeling techniques were employed within the study segment to evaluate YCT habitat availability and develop flow recommendations including Physical Habitat Simulation (PHABSIM) modeling, the Habitat Retention Method, and Habitat Quality Index (HQI) modeling. PHABSIM was used to calculate habitat availability for all life stages of YCT over a range of flow conditions. The Habitat Retention Method was used to examine riffle hydraulic characteristics needed to maintain fish passage (longitudinal connectivity) between habitat types and provide sufficient depth, velocity, and wetted area to ensure survival of fish prey items (benthic invertebrates). The Habitat Quality Index (HQI) model was used to assess the relationship between stream flow and juvenile and adult trout habitat quality in the summer. During winter months, October through April, natural flows, represented by the 20% monthly exceedance values, were recommended to maintain all life stages. Finally, a dynamic hydrograph model was used to quantify flow needs for maintenance of channel geomorphology.

Results of the instream flow investigation on Muddy Creek indicate that flows ranging from 1.3 cubic feet per second (cfs) during the winter to 29 cfs during spring are needed to maintain YCT habitat in the segment. If this instream flow application advances to permit status, approximately 3.1 miles of stream habitat in Muddy Creek will be directly protected allowing for YCT spawning, passage, and year round survival.

## **Introduction**

Rivers and streams, and their associated fisheries, are important to the residents of Wyoming, as evidenced by the passage of the Wyoming Statute 41-3-1001-1014 allowing protection of stream flows for fisheries with instream flow water rights. The Wyoming Game and Fish Department (WGFD) works to protect fisheries throughout the state using various tools and strategies, including proposing instream flow water rights where it is appropriate and beneficial. Detailed background information on instream flows in Wyoming is presented in Appendix A. Guidance for selecting streams to evaluate for instream flow water right consideration is provided by WGFD's Water Management Plan (Robertson and Annear 2011).

One of the highest current priorities for new instream flow projects are streams containing Yellowstone cutthroat trout (YCT; *Oncorhynchus clarki bouvieri*). Among the streams that contain populations of YCT, several have modified habitat conditions that have restricted the YCT populations to isolated reaches relative to the watershed-wide distributions that the species once inhabited. These remaining isolated reaches are important for conservation efforts, including maintaining sufficient stream flow to ensure long-term persistence to the extent allowed within the current interpretation of the instream flow statute.

Muddy Creek was identified as a high priority area for securing an instream flow water right for the preservation and maintenance of YCT. Muddy Creek occurs within a "crucial" habitat area as identified in the WGFD Strategic Habitat Plan (SHP) (WGFD 2009) and a "conservation area" in the WGFD State Wildlife Action Plan (2010). According to the SHP, "crucial habitats have the highest biological values, which should be protected and managed to maintain healthy, viable populations of terrestrial and aquatic wildlife. These include habitats that need to be maintained as well as habitats that have deteriorated and should be enhanced or restored." In addition, Muddy Creek contains a core conservation population of YCT as defined by the multi-state recovery team, which indicates that it is genetically pure and has the potential for reproductive exchange with other YCT populations in the stream network (May et al. 2007).

This report details the results of the Muddy Creek instream flow study conducted in July through September 2014. Flow recommendations are based upon consideration of the five primary riverine components that influence the characteristics of a stream or river: hydrology, biology, geomorphology, water quality and connectivity (Annear et al. 2004). Maintaining sufficient water of good quality is essential for sustaining fish productivity in streams and rivers. When water resources are developed in Wyoming for out-of-stream, consumptive uses, there are corresponding changes in riverine components that alter the ability of a stream to support fisheries habitat. The five riverine components were evaluated using various models and data sources to generate the recommendations for how much flow should remain in Muddy Creek (when naturally available) to provide sufficient habitat during important time periods in the life stages of YCT.

The objective of this study was to quantify instream flow levels needed to maintain YCT habitat in Muddy Creek during important seasonal periods. In addition, a channel maintenance flow regime was modeled that will maintain long-term trout habitat and related physical and biological processes (Appendix B). The information can be used as supporting material for an instream flow water application. The audience for this report includes the Wyoming State Engineer and staff, the Wyoming Water Development Office, aquatic habitat and fishery managers, and non-governmental organizations and individuals interested in instream flow water rights.

## Study Area

Muddy Creek, located in Park County Wyoming, is a tributary of the Clarks Fork River (Figure 1). The stream is located within the Cody region of the WGFD. The watershed (HUC12 100700060301) encompasses approximately 35.5 square miles. Land ownership in the watershed includes 99% Forest Service land and 1% private ownership. The private land is located at the downstream end of Muddy Creek, below the proposed instream flow segment.

The highest point in the Muddy Creek watershed is approximately 10,530 ft and the lowest point, at the downstream end of the study segment, is approximately 7,440 ft. Annual precipitation averaged 17.6 inches in the area of the stream over the period 1895–2012 according to data retrieved from the Wyoming Water Resources Data System (WRDS 2015).

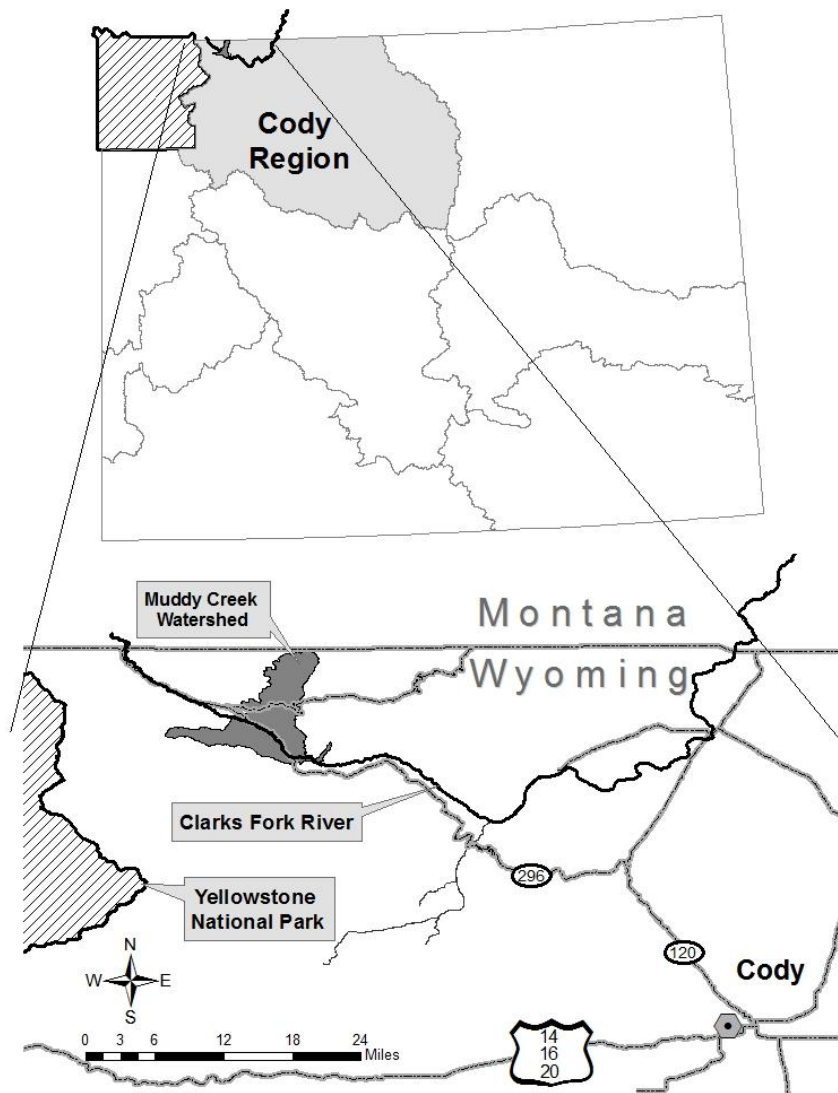


FIGURE 1. Location of Muddy Creek, WY (HUC 100700060301).

The fish community in Muddy Creek includes two species within the proposed instream flow segment, YCT and brook trout (*Salvelinus fontinalis*; BKT). The reach is isolated from the Clarks Fork River by a natural waterfall at the downstream end of the instream flow segment. This migration barrier has prevented rainbow trout (*Oncorhynchus mykiss*; RBT) from accessing the instream flow segment. Where RBT coexist with YCT in the Clarks Fork drainage, the YCT population has often been compromised with hybridization and reduced abundance. The current management objective is to maintain a wild population of YCT in Muddy Creek. Evaluation of flow conditions that are necessary to maintain or improve this fishery was conducted using the habitat and hydrological modeling efforts described below.

## Methods

### *Instream Flow Segment and Study Site Selection*

One stream segment is proposed for an instream flow water right filing in Muddy Creek (Table 1; Figure 2). The boundaries for the segment were identified after considering land ownership, hydrology, and stream channel characteristics. The downstream end of the segment is at a waterfall that serves as a complete migration barrier to the YCT population upstream. This waterfall occurs approximately 1.5 miles upstream from the confluence with the Clarks Fork River. The proposed instream flow segment extends to the Shoshone National Forest wilderness boundary approximately 3.1 miles upstream of the waterfall. The instream flow segment selected on Muddy Creek is located entirely on public land.

TABLE 1. Location, length, and elevation at the downstream end of the proposed instream flow segment on Muddy Creek.

Segment	Description	Length (mi)	Elevation (ft)
Muddy Creek	Begins at the downstream boundary of the Yellowstone cutthroat trout population (a waterfall) and extends upstream to the wilderness boundary.	3.10	7,440

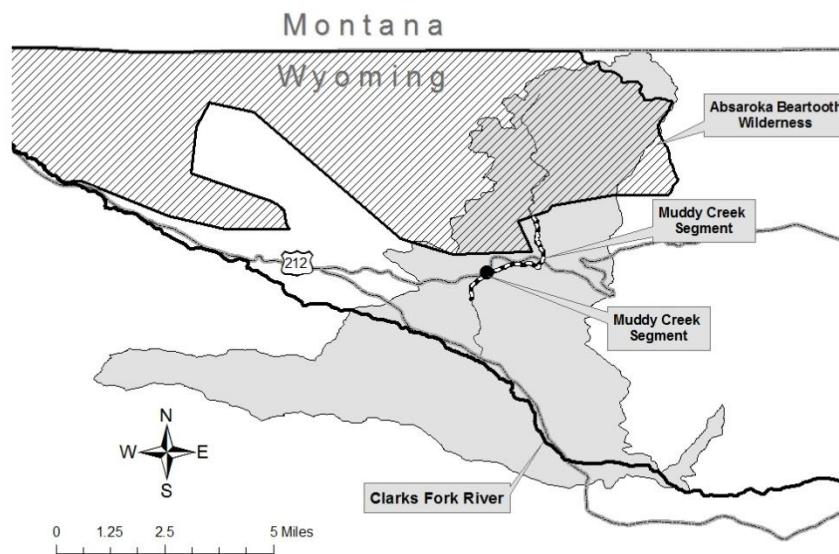


FIGURE 2. Location of Muddy Creek instream flow segment and study site.

Within the instream flow segment, one study site of approximately 250 feet of stream was selected to represent habitat conditions in the segment. Because the bankfull width in this reach was approximately 22 ft, the study site length was equal to approximately 11 times the channel width; this is within the reach length recommended by Bovee (1982; 10-14 times the channel width).

The study site included three distinct sections (e.g., riffle-run-pool or riffle-pool sequences) characterized by a total of seven cross-sections divided among them (Figure 3). The seven transects included three riffles, one run and three pools and were placed such that a riffle transect created the downstream boundary of each of the three short reaches and transects placed in appropriate upstream locations to represent the range of conditions in each reach. The complexity of this study site is representative of the range of habitat conditions available throughout the instream flow segment. All data collection was conducted in this study site and extrapolated to the entire proposed instream flow segment.



FIGURE 3. One of seven transects at the Muddy Creek study site.

### ***Hydrology***

Development of flow recommendations for an instream flow study segment requires an understanding of hydrology within the study segment. There are no stream gage data available within the segment so flow conditions were estimated from a regional reference gage (see Appendix C for details). The USGS gage on Soda Butte Creek, MT (06187915) was selected as the reference gage for these analyses (Figures 4, 5); the period of record used for analysis was 1999 to 2015. This gage was active during the study period and based on proximity, it is suspected that precipitation and runoff patterns are similar between the reference gage and the study site.

The estimates of the hydrologic characteristics in the instream flow segment were used in several ways. Average daily flow estimates were used in applying the Habitat Quality Index and Habitat Retention Models (described below). The 1.5-year return interval on the flood frequency series was used to estimate bankfull flow (Rosgen 1996) for use in the Habitat Retention Model and for developing channel maintenance flow recommendations (Appendix B). Channel maintenance calculations required the 25-year peak flow estimate from the flood frequency analysis. In addition, the monthly flow duration curve was used in developing winter flow recommendations. Flow duration curves indicate that percent of time that a given flow is equaled or exceeded. The 20% exceedance flow was identified for this analysis, which refers to the flow level that would be available approximately one year out of every five consecutive years.

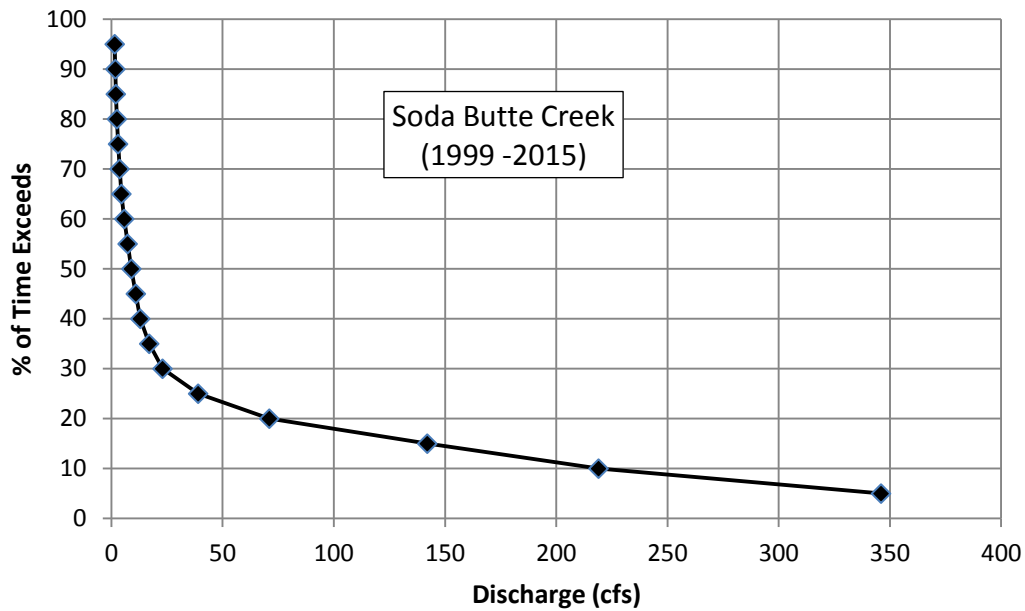


FIGURE 4. Flow exceedance curve for the Soda Butte Creek USGS stream gage station (06187915) over the period of record (1999-2015).

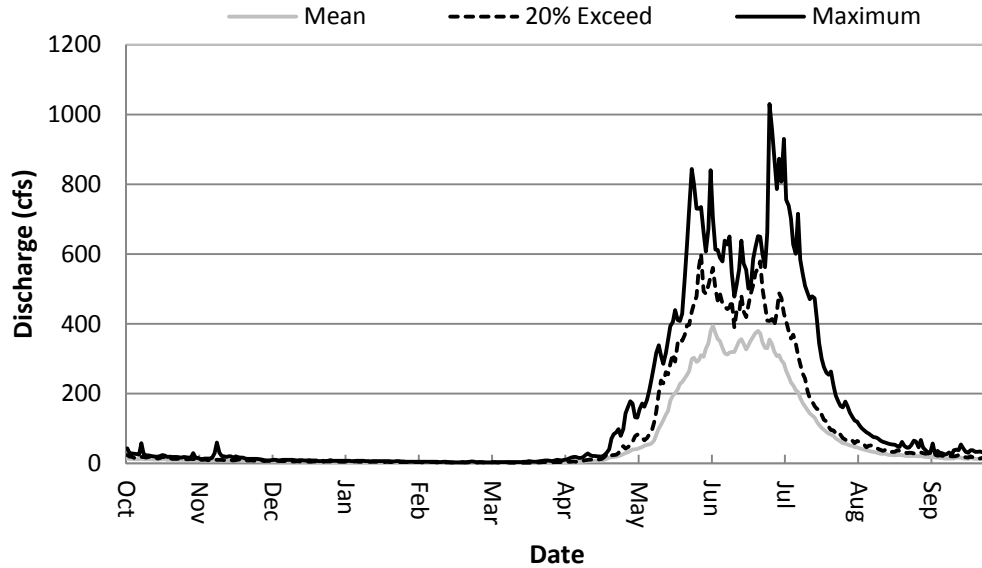


FIGURE 5. Hydrograph showing the mean, 20 percent exceedance, and maximum daily discharge for each day over the period of record (1999-2015) at the Soda Butte Creek USGS stream gage station (06187915).

In addition to estimates of local hydrology based on the regional reference gage data, a temporary stream gage station was installed within the study site between July 10, 2014 and September 27, 2014. These data provide a detailed look at the hydrologic variability during the study period and assist in selecting the appropriate regional reference gage. The gage was located upstream of a stable hydraulic control and a staff plate with 0.01 ft increments was placed in the stream in a location with minimal surface turbulence. The pressure transducer used for water level monitoring at 15-minute intervals was placed in a perforated PVC pipe which served as the stilling well. The pipe was anchored to a metal t-post and mounted vertically within the water column. Discharge measurements in the stream reach were collected over a wide range of flow conditions including high flows shortly after runoff and base flows near the end of the study period. The discharge measurements and corresponding readings on the staff plate were used to develop a local rating curve. The rating curve was used to convert the water level readings from the pressure transducer to discharge estimates during the study period.

### ***Biology – Fish Habitat Modeling***

Habitat preferences of target fish species, including each of their life stages, are important in instream flow studies since flow recommendations are based on maintaining sufficient habitat for target species to survive, grow, and reproduce. Species-specific habitat preferences are used to develop habitat suitability curves (HSCs) that are in turn used in habitat models.

Availability of fish habitat in the study site was evaluated using several different habitat models. “Habitat” in this report refers to the combination of physical conditions (depth, velocity, substrate, and cover) for a given area. These physical conditions vary with discharge. It is important to note that these variables do not represent a complete account of all variables that comprise trout habitat. Habitat for trout also includes environmental elements such as water temperature, dissolved oxygen, and other variables. These other variables are important, but are not included in models used for these analyses because they do not fluctuate with changes in the quantity of flow as predictably as the physical habitat parameters. Interpretation of model results based on these physical habitat parameters assumes that this subset of trout habitat is important and provides a reasonable indication of habitat availability at each flow and an indirect expression of the ability of trout to persist on at least a short-term basis at those flow levels.

Dey and Annear (2006) found that adult YCT in Trout Creek (tributary of the North Fork Shoshone River) were most commonly found in areas with depths of 1.15–1.60 ft and average column velocities of 0.36–1.91 ft/s. For juvenile YCT, these ranges were slightly different with depths of 1.0–1.5 ft and average column velocities of 0.38–1.65 ft/s (Dey and Annear 2006). Growth rate of adult and juvenile YCT is greatest during the relatively short summer and early fall periods. Habitat for these life stages is also critical during winter to allow over-winter survival.

During spawning, YCT use different habitat conditions than during other life history stages. YCT spawn between March and July throughout their range, depending on local hydrology and water temperatures (believed to be triggered around 41°F; Kiefling 1978, Varley and Gresswell 1988, De Rito 2005). The stream gradient observed in spawning areas is usually less than 3% (Varley and Gresswell 1988), but non-migratory fluvial populations have been documented in streams with a mean gradient of 6% (Meyer et al. 2003). Spawning activity for YCT in Wyoming has been observed during May and June in watersheds within the Bighorn River Basin in north central Wyoming (Greybull River, Shoshone River and their tributaries; Kent 1984, Dey and Annear 2002, Dey and Annear 2006). Elevation has an influence on the

timing of spawning in YCT with stream segments located at higher elevations more likely to remain colder and cause delayed spawning and slower egg incubation rates. Dey and Annear (2003) found that spawning in the Greybull watershed occurred into July in streams above approximately 8,000 ft in elevation and extended recommendations for spawning flows through July 15 in such high elevation sites. The instream flow segment on Muddy Creek occurs from about 7,440 ft in elevation to about 8,100 ft on the upper end so it is likely that spawning occurs into July in the segment. Dey and Annear (2006) observed too few spawning YCT (n=4) to develop habitat suitability curves for spawning YCT in Wyoming. Spawning YCT habitat suitability data from a Snake River tributary in Idaho are presented in Thurow and King (1994); these researchers found that velocity preference was highest from 1.12 to 1.72 ft/sec and depth preference highest from 0.52 to 0.82 ft. Information from that study was used to indicate habitat selectivity of YCT in Muddy Creek.

### **Physical Habitat Simulation Model**

The Physical Habitat Simulation (PHABSIM) model (Bovee et al. 1998) was used to estimate how much habitat is available for individual life stages of YCT at different stream flow levels. The results of the model were evaluated to determine how much stream flow is needed to maintain sufficient habitat for these life stages during critical time periods.

The PHABSIM model calculated a relative suitability index for YCT based on depth, velocity, and substrate. Model calibration data were collected on seven transects including three riffles, three pools and one run. Along each transect, depth and velocity were measured at multiple locations (cells); spacing was determined based on substrate characteristics and the cross-section depth profile. Measurements were taken in the same cells at three different discharge levels (7.8 cfs, 4.2 cfs, and 3.4 cfs). Calibrating the model involved adjustments to hydraulic and velocity model parameters to provide the best estimation of conditions relative to observations at the different flows measured in the field (Bovee et al. 1998).

Simulations were conducted using a calibrated PHABSIM model over the flow range 0.50 cfs to 160 cfs. Using the depths and velocities measurements along each transect at the calibrated flow levels, the PHABSIM model predicted depth and velocity values at these same locations for each simulated discharge level (Bovee and Milhous 1978, Milhous et al. 1984, Milhous et al. 1989). These predicted depths and velocities, along with substrate or cover information, were compared to HSCs of the target species to determine how much suitable habitat occurs at each flow.

The amount of suitable habitat or weighted usable area (WUA) for each stream flow and life stage combination was calculated using the HSCs for depth, velocity, substrate, and cover which range between “0” (no suitability) and “1” (maximum suitability) for each life stage. A suitability value was assigned to each cell for each HSC based on the simulation results for a given discharge. A combined suitability was generated and multiplied by the surface area of the cell. The sum value of all cells yielded the WUA for the simulated discharge level. Data from the seven transects grouped into three sections; each section was given equal weighting toward the total estimate of WUA for each flow.

Results were displayed by graphing WUA for a particular fish life stage versus a range of simulated discharges (Bovee et al. 1998). The values were normalized to a percent of the maximum WUA value as recommended by Payne (2003).

### **Habitat Retention Model**

The Habitat Retention Model (Nehring 1979, Annear and Conder 1984) was used to evaluate hydraulic characteristics that affect the survival and movement of all life stages over a range of discharges in the Muddy Creek instream flow segment. The model was used to identify the lowest flow that maintains specified hydraulic criteria in riffles (Table 2). These criteria represent conditions needed to maintain fish passage, or longitudinal connectivity, among habitat types and ensure sufficient depths, velocities, and wetted areas for the survival of benthic invertebrates, many of which serve as fish prey (Nehring 1979). Flow recommendations derived from the Habitat Retention Method address portions of the connectivity and biology riverine components. The flow identified by the Habitat Retention Method is important year round, except when greater flows are necessary to meet other behavioral or physiological requirements of the target fish species.

Simulation tools and calibration techniques used for hydraulic simulation in PHABSIM are also used with the Habitat Retention Method. The AVPERM model within the PHABSIM methodology was used to simulate cross section depth, wetted perimeter and velocity for a range of flows. The flow that maintains two out of three criteria for all modeled transects is then identified as the threshold to maintain sufficient flow to meet the needs of the fishery. Because of the critical importance of depth for maintaining fish passage, the 0.2 ft threshold was required to be one of the criteria met for each transect (Table 2). Because Muddy creek is wider than 20 feet (mean bankfull width from the three transects) the mean depth criterion was 0.01 times the mean bankfull width.

TABLE 2. Hydraulic criteria for determining maintenance flow with the Habitat Retention Method (Annear and Conder 1984).

Category	Criteria
Mean Depth (ft)	0.20 <sup>a</sup>
Mean Velocity (ft/s)	1.00
Wetted Perimeter <sup>b</sup> (%)	50

a – when transect bankfull width >20 ft, then 0.01 \* mean bankfull width

b – Percent of bankfull wetted perimeter, calculated by transect

### **Habitat Quality Index Model**

The Habitat Quality Index (HQI; Binns and Eiserman 1979, Binns 1982) was used to determine production potential of adult and juvenile YCT in the study site during summer (July through September) flow conditions. Most trout production (growth) in Wyoming streams occurs during summer, following peak runoff, when longer days and warmer water temperatures facilitate growth. Developed by the WGFD, the HQI model uses nine biological, chemical, and physical trout habitat attributes estimate relative habitat suitability in a stream reach and can be used to predict trout abundance.

For this study, the HQI was used to estimate the number of YCT habitat units in the study reach, each of which is expected to support about 1 pound of trout. Data were collected for HQI calculations at 7.8 cfs, 4.2 cfs, and 3.4 cfs between July 1 and September 30 and attribute ratings were interpolated between these measurements to characterize the relationship

between discharge and trout habitat conditions at discharges other than those measured (Conder and Annear 1987).

Article 10, Section d of the Wyoming Instream Flow statute states that waters used for providing instream flow water rights “shall be the minimum flow necessary to maintain or improve existing fisheries.” To maintain a viable trout fishery, it is critical to maintain normal late summer flows, which are represented by the September 20% monthly exceedance flow. The HQI results were used to identify the number of habitat units that occur at this flow and the lowest flow that maintains that quantity of habitat.

### **Natural Winter Flow**

Low water temperature, which reduces metabolic rates, reduced living space associated with naturally lower flow conditions during this season, and the lack of food are all factors that make the winter a stressful time period for fish in Wyoming Rocky Mountain headwater streams (Locke and Paul 2011). Even relatively minor flow reduction at this time of year can change the frequency and severity of ice formation, force trout to move more frequently, affect distribution and retention of trout, and reduce the holding capacity of the few large pools often harboring a substantial proportion of the total trout population (Lindstrom and Hubert 2004).

The habitat modeling approaches described above are not well suited to determine flow requirements during ice-prone times of year. These methods were all developed for and apply primarily to open-water periods. Ice development during winter months can change the hydraulic properties of water flowing through some stream channels and compromise the utility of models developed for open water conditions. The complexities of variable icing patterns make direct modeling of winter trout habitat over a range of flows difficult if not impossible. For example, frazil and surface ice may form and break up on multiple occasions during the winter over widely ranging spatial and temporal scales. Even cases that can be modeled, for example a stable ice cap over a simple pool, may not yield a result worthy of the considerable time and expense necessary to calibrate an ice model. There are no widely accepted aquatic habitat models for quantifying instream flow needs for fish in under-ice conditions (Annear et al. 2004). As a result, a different approach was used to develop recommendations for winter flows.

To determine the winter flow necessary to maintain the YCT fishery in Muddy Creek, the 20% monthly exceedance value for all winter months was averaged. Whereas other flow values may be sufficient to support the fishery at other times of the year, the 20% monthly exceedance flow is most appropriate in winter. Hubert et al. (1997) observed that poor gage records often associated with the winter season requires use of a conservative value. Their studies showed that 50% monthly exceedance does not provide an appropriate estimate of naturally occurring winter flow. This approach assures that even in cases where flow availability is underestimated due to poor gage records or other estimation errors, flow approximating the natural winter condition will be protected.

### ***Geomorphology***

Maintaining appropriate stream channel characteristics in a given stream reach is important for preventing loss of fish habitat throughout that stream. Reductions in flow quantity can affect the sediment load balance such that its transport capacity is diminished and excess fine sediments aggrade in the channel (Bovee et al. 1998). This usually reduces habitat suitability for fish communities. Other physical changes in the stream caused by road building, culvert addition, riparian habitat reduction, and other activities also affect sediment transport dynamics.

In streams compromised with streambank instability that have additional sediment inputs from land management practices (grazing and channel alterations) and road construction and maintenance activities in the watershed, reduction in natural flow conditions makes it even more difficult for the stream to move sediment sufficiently to prevent aggradation.

The geomorphology conditions of the proposed instream flow segment were evaluated by visual observation. Observations on channel form characteristics including Rosgen channel type, sinuosity, and riparian habitat conditions were noted. In addition, roads, culverts and other changes to the watershed were identified along with areas of excessive erosion and any imbalance in sediment load conditions. This visual assessment also included observations on the influence of substrate sizes and large woody debris on pool development and habitat conditions for the fish community.

An evaluation of high flows that are important for channel maintenance and necessary to maintain existing fisheries on a long-term basis was not included in the main body of the report since the current interpretation of the instream flow statute does not allow issuance of water rights for high flows. Recommendations for flows sufficient to allow channel maintenance and to fully maintain fishery habitat in the segment are presented in Appendix B. Should opportunities arise in the future to secure instream flow water rights for long-term maintenance of stream habitat conditions, this information will provide a valuable reference.

### ***Water Quality***

Water temperature in late summer and fall has been found to be a limiting factor for many trout populations and this data is critical to consider in development of an instream flow recommendation. The evaluation of water quality in the proposed instream flow segment included collecting water temperature in the study reach between July 10 and September 27, 2014 with a logger that recorded water temperature every 15 minutes. These water temperature data were compared with NorWeST model results generated by the USFS Rocky Mountain Research station (<http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>). That model is based on data collected at various points throughout the Yellowstone River HUC6 watershed (100700), including the Upper Clarks Fork catchment, and estimates water temperature in all streams and tributaries throughout the watershed.

In addition, a Nitrate + Nitrite-N sample was collected and analyzed by the Wyoming Department of Agriculture Analytical Services Laboratory. Finally, the Wyoming Department of Environmental Quality classification was noted and any sampling conducted by that agency or any other entities (using the EPA STORET database) to determine existing water quality conditions and the potential for deterioration with reduced water flow was considered as part of the evaluation.

### ***Connectivity***

River system connectivity is manifested along four dimensions: longitudinal, lateral, vertical, and temporal (Ward 1989). Lateral connectivity is critical to the functioning of floodplain-based stream ecosystems due to the transport of nutrients and organic matter from the floodplain to the stream during floods. This process is important in population dynamics of aquatic insects and ultimately affects fish productivity. The seasonal flooding of unregulated streams creates and maintains diverse species of riparian vegetation (Nilsson et al. 1989), which increases stream channel stability and fosters diverse animal communities both within and adjacent to the stream channel.

In developing instream flow recommendations for the proposed segment, the presence of barriers to connectivity were considered for physical, chemical, and even biological conditions in all four dimensions. The Habitat Retention Method was used to quantify the flow needed to maintain longitudinal hydrologic connectivity within the stream channel. However, no detailed assessment was conducted to quantify flows needed to maintain lateral connectivity nor was an assessment done to evaluate the relationship between ground water and flow (vertical connectivity) because of the difficulty in evaluating these connections. Though the ability of the stream to transport of nutrients, energy and sediments was beyond the technical and legal scope of this study, this process is important in a properly functioning stream environment.

### ***Instream Flow Recommendations***

Data from the evaluation of all five riverine components were considered in developing instream flow recommendations for YCT in Muddy Creek. However, Wyoming statute 41-3-1001-1014, which declares that instream flows may be appropriated for maintaining or improving fisheries, has been interpreted by Wyoming state engineers to include only hydrology and fisheries components of streams. This interpretation limits the ability to include the other riverine components (geomorphology, water quality, and connectivity) as a basis for quantifying flow regime needs for maintaining fisheries. Though not specifically included in the flow recommendations, information on these other important riverine components on Muddy Creek is presented in this report including a detailed discussion of channel maintenance flows in Appendix B. The recommendations resulting from these analyses are expected to maintain short-term habitat for YCT in Muddy Creek, but do not consider changes in natural geomorphic characteristics and habitat forming processes of the stream that are expected to occur over time intervals of decades or longer. Consequently, these flow recommendations may not fulfill the statutory opportunity to maintain or improve the existing fishery on a long-term basis (perpetuity).

Instream flow recommendations were generated for three seasonal periods that are critical to the various life stages of YCT in Muddy Creek. The timing and duration of each seasonal period is based on YCT biology and hydrology information from the reference gage (Table 3; Figure 6). Over-winter survival of adult and juvenile YCT is addressed with natural winter flow from October 1 through April 30. The estimated hydrograph indicates that, on average, relatively low base flow conditions in winter persist through late-April during both the highest and lowest flows recorded. Spawning and incubation habitat for YCT is quantified using PHABSIM habitat modeling results for the period May 1 to July 15. Summer habitat for growth and production of adult and juvenile YCT is quantified with Habitat Quality Index results and PHABSIM modeling results for the period July 16–September 30.

The models used for developing the recommendation for a given season were selected based on their appropriateness for the characteristics and flow needs at the study site. Some models (e.g., Habitat Quality Index) are more suited to certain life stages and time periods so each was used during the season that was most appropriate. In some cases, the ecological characteristics and issues at a study site were unique and models used for developing flow recommendations in other studies were not necessarily appropriate in this situation. When two or more methods were appropriate for developing a flow recommendation, the one that yielded the higher flow requirement was chosen.

TABLE 3. Yellowstone cutthroat trout life stages and seasons considered in developing instream flow recommendations. Numbers indicate the method used for each combination of season and life stage, and gray shading indicates the primary data used for flow recommendations in each season.

Life stage and Fishery Function	Over-Winter Oct 1 – Apr 30	Spring May 1 – Jul 15	Summer Jul 16 – Sep 30
Survival of all life stages	1		
Connectivity between habitats	2	2	2
Adult and juvenile habitat availability	3	3	3
Spawning habitat availability		3	
Adult and juvenile growth			4
Habitat maintenance for all life stages*		5	

1=Natural winter flow or Habitat Retention, whichever is greater, 2=Habitat Retention, 3=Physical Habitat Simulation, 4=Habitat Quality Index, 5=Channel Maintenance.

\* Channel maintenance flow recommendations are presented in Appendix B.

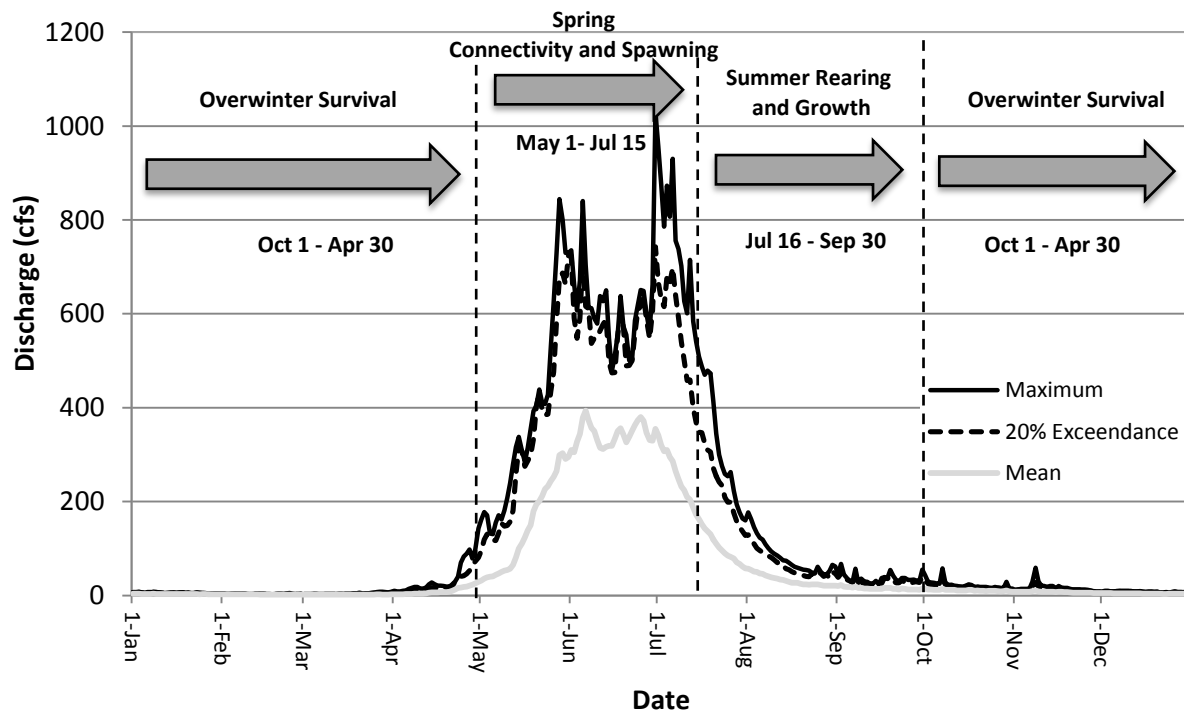


FIGURE 6. Minimum and maximum daily historical discharge values over the period of record at the reference gage with critical time periods for YCT distinguished. Discharge data are from the USGS stream gage on Soda Butte Creek (06187915).

## Results

### Hydrology

Streamflow at the reference gage was high in 2014. At 92.2 cfs, mean discharge for the year was the second highest in the 16 year period of record. On the Lamar River (USGS gage 06188000) to the west, mean annual discharge in 2014 ranked as the ninth highest flow year over a 72 year period of record. The high flows delayed the onset of the field study as runoff occurred later and over a longer time period than during normal or low flow years. Base flows in the fall also may not have been as low as in other years. Nonetheless, all necessary data were collected to complete the study.

Mean annual flow was estimated to be 11.0 cfs in the Muddy Creek instream flow segment; flood frequency analysis indicates that the 1.5-year peak flow is 118 cfs and the 25 year peak flow is 238 cfs (Table 4). Monthly flow duration estimates, including 50% and 20% exceedance values, are displayed in Table 5. Discharge data collected during the study are presented in Table 6. In addition, a hydrograph was prepared that shows the mean, 20 percent exceedance, and maximum daily discharge estimate over the period of record in the study site (Figure 7).

TABLE 4. Estimated hydrologic characteristics for the Muddy Creek instream flow segment.

Flow Parameter	Estimated Flow (cfs)
Mean Annual	11.0
1.5-year peak	118
25-year peak	238

TABLE 5. Estimated monthly exceedance values for the Muddy Creek instream flow segment.

Month	50% Exceedance (cfs)	20% Exceedance (cfs)
October	1.7	2.5
November	1.2	1.6
December	0.7	0.9
January	0.5	0.7
February	0.4	0.5
March	0.3	0.4
April	0.9	2.8
May	17	43
June	57	80
July	21	42
August	4.4	7.6
September	2.1	3.2

TABLE 6. Dates of collection and discharge measurements collected in the Muddy Creek instream flow segment in 2014.

Date	Discharge (cfs)
7/10/14	30.0
7/27/14	7.8
8/14/14	4.2
9/27/14	3.4

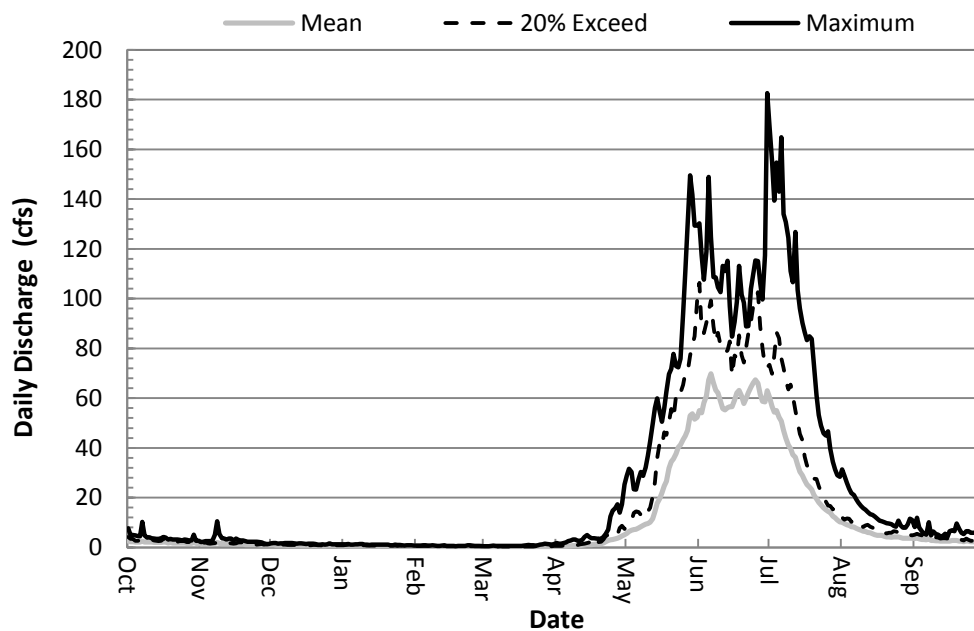


FIGURE 7. Hydrograph showing the mean, 20 percent exceedance, and maximum daily discharge estimates for the Muddy Creek study site.

The temporary stream gage in the Muddy Creek study site allowed estimates of daily discharge during the study period. A total of four stage and discharge pairs between 3.4 cfs and 30 cfs were collected to create the rating curve (Figure 8). This rating curve ( $y = 0.4256x^{0.4219}$ ) was applied to the water level data recorded from the pressure transducer to generate an estimate of instantaneous and daily discharge values (Figure 9).

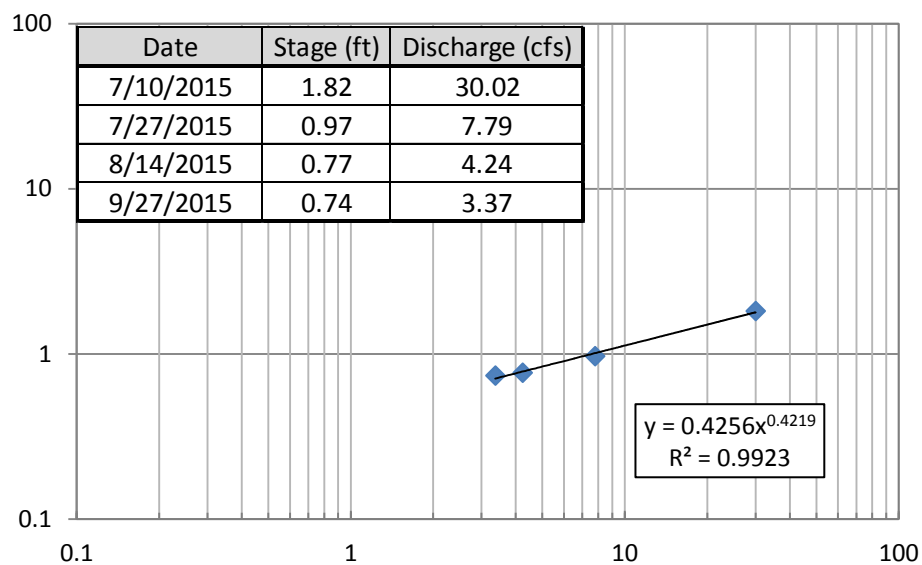


Figure 8. Rating curve data for the temporary gage established at the Muddy Creek study site during 2014.

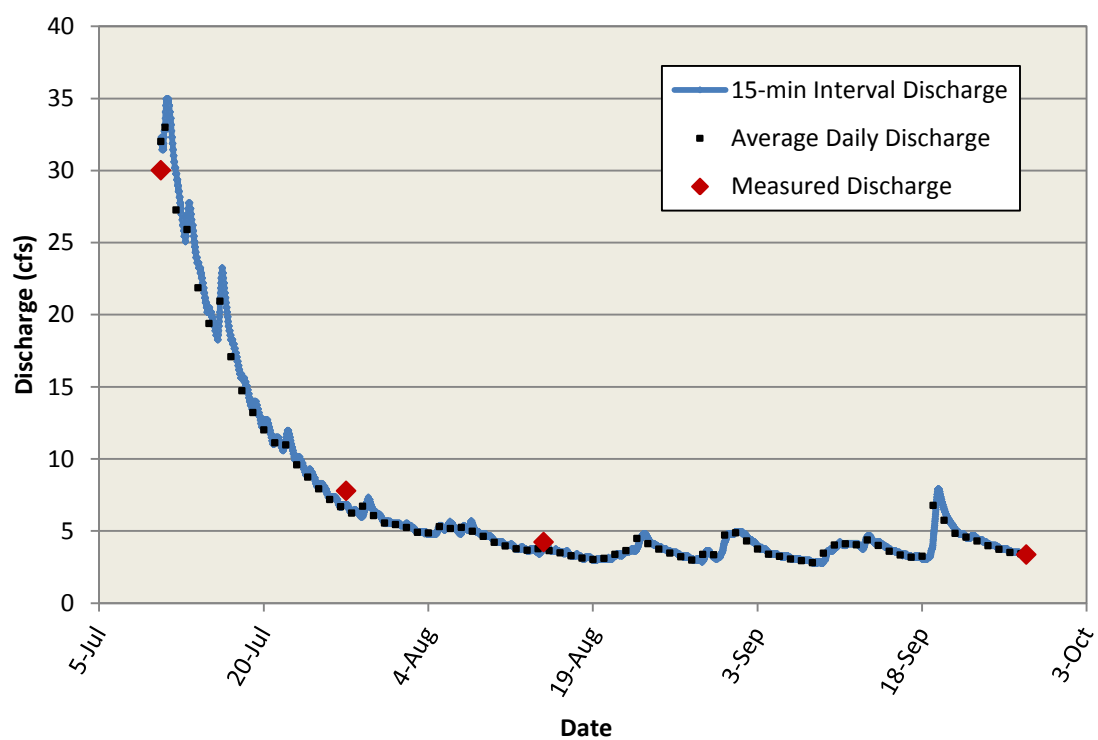


Figure 9. Estimated hydrograph for Muddy Creek study site during 2014.

## Biology – Fish Habitat Modeling

### Physical Habitat Simulation Model

The PHABSIM model was used to estimate habitat for adult, juvenile and spawning life stages of YCT. The model results indicated that for the adult life stage, WUA increases rapidly with increasing flow up to 25 cfs and remains high up to about 40 cfs before decreasing slowly with additional increases in flow (Figure 10). The juvenile life stage has a similar increase in habitat up to 35 cfs and also decreases slowly above 40 cfs. The lowest flow that maintained 95% or more of the WUA both adult and juvenile life stages was 29 cfs. For the spawning life stage, WUA is very low up to 10 cfs, increases rapidly to a peak at 50 cfs, and then begins to decline after that point; however, this study reach had little suitable spawning habitat.

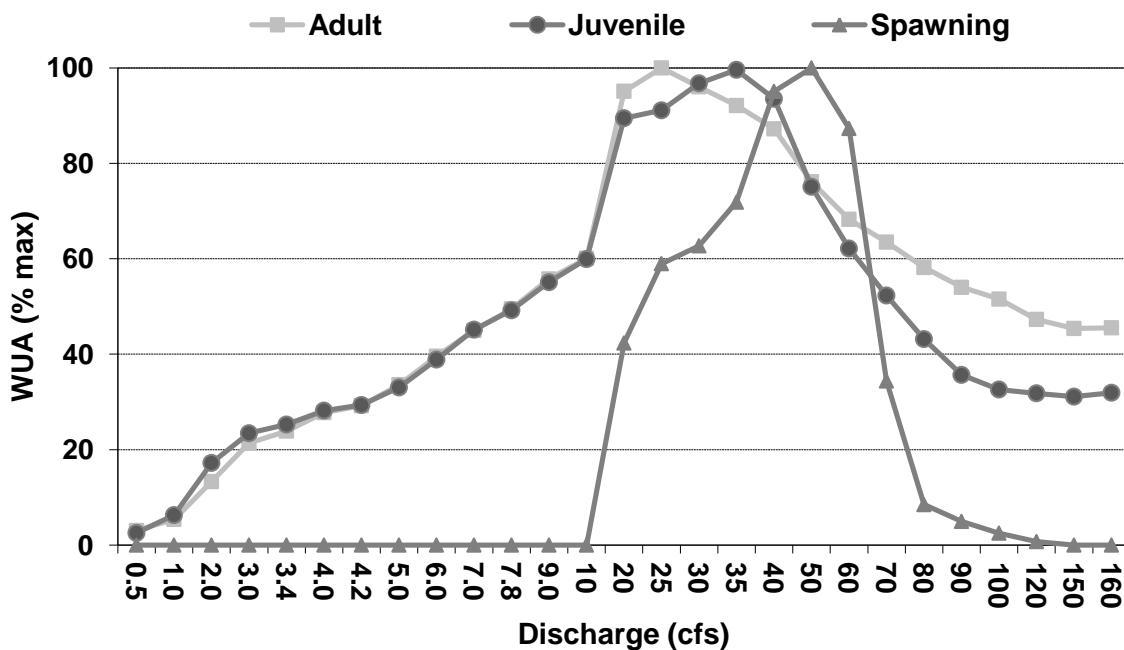


FIGURE 10. Relationship between WUA and discharge for YCT adult, juvenile and spawning life stages in the Muddy Creek study site. X-axis values are not to scale; the values were chosen to highlight important habitat conditions.

### Habitat Retention Model

The Habitat Retention Model was used to evaluate hydraulic characteristics that affect the survival and movement of all life stages over a range of discharges in the Muddy Creek instream flow segment (Table 7). Three riffle cross-sections, with an average bankfull discharge of 155 cfs, were modeled and the resulting discharge needed to maintain the necessary hydraulic criteria was 3.8 cfs. This flow should maintain base level conditions for fish passage and provide

habitat for benthic invertebrate populations on riffles with similar characteristics as the riffle cross-section, though higher flows at some times of year may be needed for other fishery purposes.

TABLE 7. Estimated hydraulic conditions for three riffles over a range of modeled discharges in the Muddy Creek instream flow segment. Bold indicates that the hydraulic criterion was met for an individual attribute; the grayed-out discharge value meets the selection criteria. Bankfull discharge was estimated to be 155 cfs.

Riffle Transect Number	Discharge (cfs)	Mean Velocity (ft/sec)	Mean Depth (ft)	Wetted Perimeter (% of bankfull)
1	155	3.02	2.11	1.00
	14	<b>1.01</b>	0.80	0.70
	<b>3.8</b>	0.76	0.41	<b>0.50</b>
	3.0	0.73	0.38	0.45
	2.0	0.70	0.29	0.40
	1.0	0.70	<b>0.23</b>	0.26
2	155	6.15	1.18	1.00
	10	1.21	0.46	0.81
	7.7	<b>1.00</b>	0.44	0.79
	3.0	0.51	0.36	0.73
	2.0	0.38	0.33	0.71
	<b>0.5</b>	0.14	<b>0.25</b>	<b>0.64</b>
3	155	3.73	1.92	1.00
	10	1.10	0.52	0.75
	7.0	<b>1.00</b>	0.40	0.73
	<b>3.6</b>	0.96	<b>0.23</b>	0.69
	2.3	1.05	0.18	<b>0.51</b>
	1.0	1.18	0.14	0.24

#### Habitat Quality Index Model

The HQI model was used to determine production potential of adult and juvenile YCT in the study site during summer (July through September) flow conditions. The 20% exceedance flow value for September (3.2 cfs; Table 5) is used as an estimate of existing late summer flow levels for this model. At this flow, the stream provides 91.4 Habitat Units. The instream flow recommendation associated with this model is the lowest streamflow value that provides as many Habitat Units as the 20% exceedance value, which in this case is 3.0 cfs (Figure 11). The model shows that long-term reductions of late summer flow to levels less than this amount would reduce the productivity of the existing fishery by over 20%.

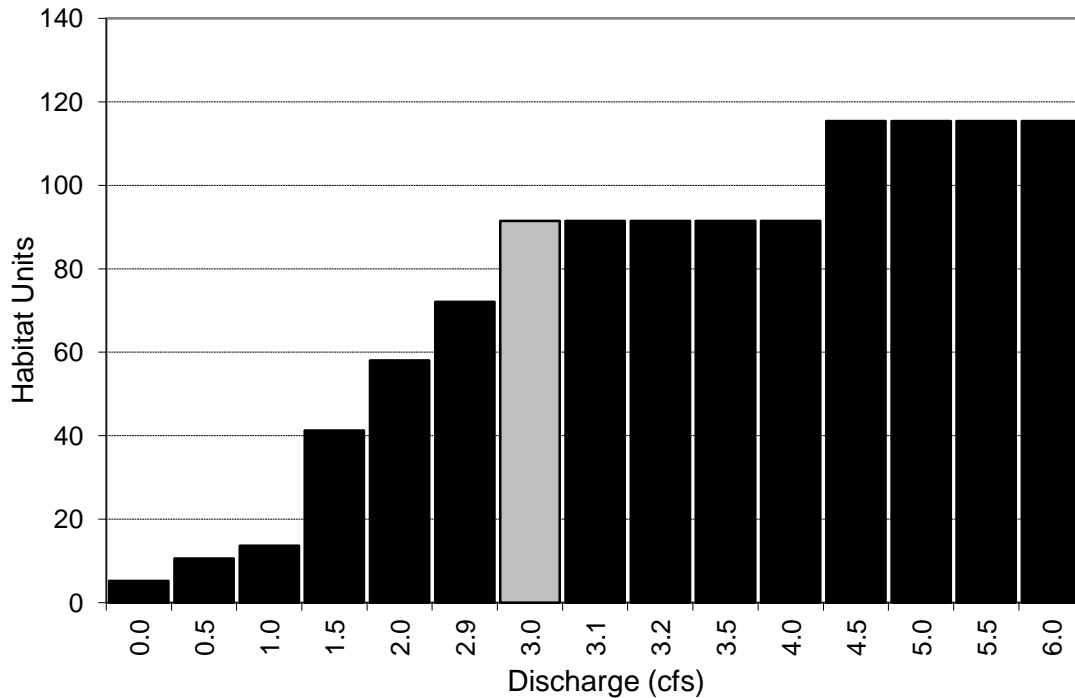


FIGURE 11. Habitat Quality Index vs. discharge in the Muddy Creek instream flow segment. X-axis values are not to scale; the values were chosen to indicate where changes in Habitat Units occur. The recommended flow (3.0 cfs) is needed to maintain the existing fishery and is indicated by the light shaded bar.

### **Natural Winter Flow**

Between October 1 and April 30, the estimated monthly 20% exceedance values in the proposed instream flow segment ranged from 0.4 cfs to 2.8 cfs (Table 5). Natural winter flows of up to 1.3 cfs, the mean of the 20% monthly exceedance discharges for the winter time period, are needed to maintain over-winter survival of all life stages of YCT at existing levels.

### ***Geomorphology***

The proposed instream flow segment in Muddy Creek includes sections of both Rosgen C-type channel and Rosgen B-type channel with a steep slope and low sinuosity. The stream is stable throughout with dense riparian habitat stabilizing the banks and large cobble and boulder substrates providing diverse habitat conditions for fish. Similarly, large woody debris contributions from the riparian forests contribute to pool development. Hydraulic controls were formed primarily by large cobbles but there were some areas with gravel substrates including moderate amounts deposited along the stream margins. There are some sections upstream of the instream flow segment where sinuosity is much higher and riparian shading substantially reduced as the stream passes through flat meadows.

A detailed description of recommended channel maintenance flows to sustain the channel form and fisheries habitat in the proposed instream flow segment over the long term is presented in Appendix B.

### ***Water Quality***

Muddy Creek is a high elevation stream located on National Forest lands and has little development within its catchment. As such, water quality conditions Muddy Creek were assumed to be favorable for supporting the fishery at most times of year and in most years. Water quality could potentially deteriorate with any substantial reduction in flow or alteration of watershed form or function. There is probably some contribution of non-point pollutants from moderate to heavy summer traffic on the road passing through the watershed, but otherwise there is nothing to suggest water quality impairment at the present time.

The maximum recorded water temperature in Muddy Creek was 58.6° F during the study period and temperature exceeded 55° F only 2.3% of the time between July 10 and September 27, 2014. The mean August temperature recorded in 2014 was 48.6° F. The NorWeST model generated by the Rocky Mountain Research Station estimates the mean August temperature to be 49.7° F at the downstream end of the Muddy Creek instream flow segment; the data collected in our study are consistent with that estimated in the NorWeST model. The NorWeST model also considers future changes in stream temperatures and predicts a mean August temperature of 51.4° F in 2040. Isaak and Hubert (2004) found that cutthroat trout abundance peaked in Wyoming streams around 53.6° F and Carlander (1969) indicates that YCT are commonly found in streams with a temperature range between 40° F and 60° F. Dwyer and Kramer (1975) found that metabolic activity peaks around 59° F. The water temperatures in Muddy Creek appear to favor YCT currently and will continue to be within suitable ranges with even a moderate increase; however, if flow were substantially reduced, water temperatures might increase to a point that YCT would be negatively impacted. Some studies have indicated that warmer water temperatures (> 60° F) provide non-native BKT a competitive advantage that would negatively impact the sympatric YCT population (De Staso and Rahel 1994; Dunham et al. 1999; Novinger 2000).

A review of the EPA STORET database did not show any water quality monitoring data from Muddy Creek or nearby streams. There were a few samples from more distant streams within Upper Clarks Fork watershed that indicated good water quality conditions. There is probably some contribution of non-point pollutants from heavy summer traffic on the road passing through the watershed but otherwise there is little to suggest water quality impairment now or in the near future. The only water quality data that were collected at the study site included a single Nitrate + Nitrite – N sample, which was analyzed by the Wyoming Department of Agriculture Analytical Services Laboratory; the result was 0.04 mg/L.

The Wyoming Department of Environmental Quality rates Muddy Creek as a “Class 2AB” water (WYDEQ 2013). According to their classification system, “Class 2AB waters are those known to support game fish populations or spawning and nursery areas at least seasonally and all their perennial tributaries and adjacent wetlands and where a game fishery and drinking water use is otherwise attainable. Class 2AB waters include all permanent and seasonal game fisheries and can be either “cold water” or “warm water” depending upon the predominance of cold water or warm water species present. All Class 2AB waters are designated as cold water game fisheries unless identified as a warm water game fishery by a “ww” notation in the Wyoming Surface Water Classification List. Unless it is shown otherwise, these waters are presumed to have sufficient water quality and quantity to support drinking water supplies and are protected for that use. Class 2AB waters are also protected for nongame fisheries, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture and scenic value uses.”

Flow recommendations in this report are expected to help maintain water quality within natural bounds and it is assumed that existing water quality features will remain within existing limits of natural variability. If drastic long-term changes to watershed form or function occur, then flow recommendations would need to be reviewed.

### ***Connectivity***

There is one road crossing and no diversion structures within the proposed instream flow segment in Muddy Creek, so longitudinal connectivity remains unimpaired. The one road crossing has a large open-bottomed culvert that appeared to be appropriately sized for the stream that it does not create a barrier to movement. There are several steep drops in the channel throughout the segment where the channel steepens dramatically and large substrates settled on the streambed. The stream appears to have access to the narrow floodplain throughout the watershed and is only limited in areas with canyon walls and little or no natural floodplain development.

Flow recommendations in this report are expected to maintain good connectivity conditions within the instream flow segment. If drastic long-term changes to watershed form or function occur, then flow recommendations would need to be reviewed.

### ***Instream Flow Recommendations***

The recommendations for specific seasonal fishery needs for the Muddy Creek instream flow segment are (Table 8; Figure 12):

- Winter (October 1 – April 30) – Natural winter flows of up to 1.3 cfs are needed to maintain over-winter survival of all life stages of YCT at existing levels. This value is the mean of the 20% monthly exceedance discharges for the winter time period (range of 0.4-2.8 cfs).
- Spring (May 1 – July 15) – Natural flow up to 29 cfs is needed to provide sufficient habitat for adult and juvenile YCT (PHABSIM results).
- Summer (July 16 – September 30) – Natural flow up to 3.0 cfs is needed based on HQI results to provide sufficient habitat conditions for growth and production of juvenile and adult YCT.

TABLE 8. Instream flow water right recommendations (cfs) for the proposed instream flow segment in Muddy Creek.

<b>Study Segment</b>	<b>Winter Oct 1 – Apr 30</b>	<b>Spring May 1 – Jul 15*</b>	<b>Summer Jul 16 – Sep 30</b>
Muddy Creek	1.3	29	3.0

\* Channel maintenance flow recommendations for the spring runoff period are defined in Appendix B.

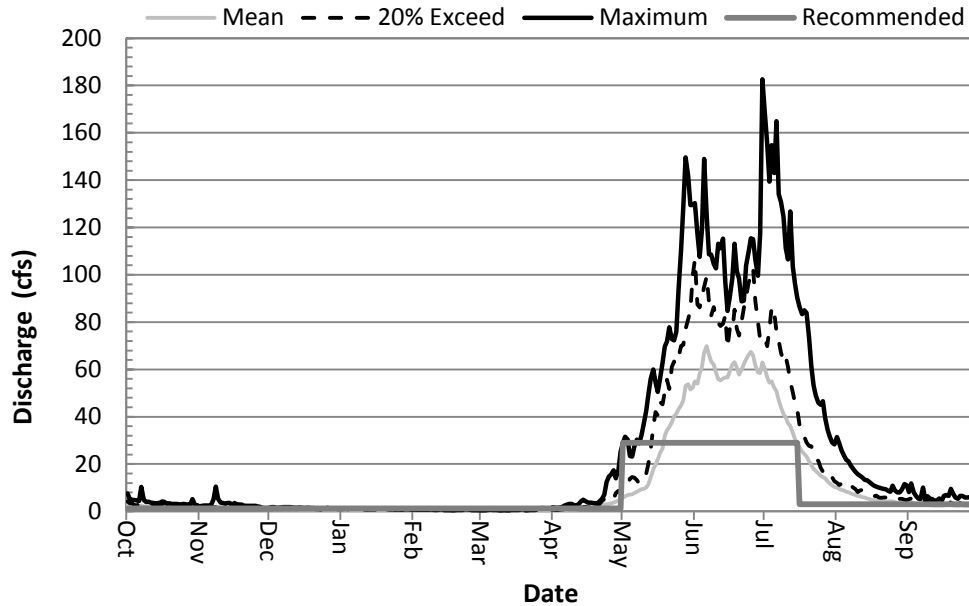


FIGURE 12. Recommended instream flow water right in the proposed segment (when naturally available) relative to mean, 20 percent exceedance, and maximum daily discharge estimates.

## Discussion

Muddy Creek provides important YCT habitat to one of the few remaining core conservation populations in the Clarks Fork River drainage. Protecting stream flows that provide this habitat and support the population of trout will help ensure the long-term persistence of the species in the Absaroka Mountains and throughout Wyoming. This action will also support the state's interests by adding to conservation actions needed to keep the species from being listed as threatened or endangered by the federal government. This YCT population is managed as a wild fishery within the Shoshone National Forest. If approved by the State Engineer, the proposed instream flow water right filing on Muddy Creek will maintain existing base flow conditions, when naturally available, against potential future out-of-channel uses up to the permitted amount. Approximately 3.1 miles of stream habitat will be directly maintained in Muddy Creek. If drastic long-term changes to watershed form or function occur, then flow recommendations would need to be reviewed to achieve the statutorily provided opportunity of maintaining or improving the existing fishery.

## Acknowledgements

Data was collected with the help of Wyoming Game and Fish Department fisheries technician Anthony Winn. Laura Burckhardt reviewed the manuscript and provided constructive comments that greatly improved the quality and clarity of the report.

## ***Literature Cited***

- Annear, T. C., and A. L. Conder. 1984. Relative bias of several fisheries instream flow methods. *North American Journal of Fisheries Management* 4:531–539.
- Annear, T., I. Chisholm, H. Beecher, A. Locke, and 12 other authors. 2004. *Instream Flows for Riverine Resource Stewardship. Revised edition.* Instream Flow Council, Cheyenne, Wyoming.
- Binns, N. A. 1982. *Habitat Quality Index Procedures Manual.* Wyoming Game and Fish Department, Cheyenne, Wyoming.
- Binns, N. A. and F. Eiserman. 1979. Quantification of fluvial trout habitat in Wyoming. *Transactions of the American Fisheries Society* 108:215–228.
- Bovee, K. D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. U.S. Fish and Wildlife Service FWS/OBS-82/26. 248 pp.
- Bovee, K., and R. Milhous. 1978. Hydraulic simulation in instream flow studies: theory and technique. Instream Flow Information Paper 5, FWS/OBS-78/33, Cooperative Instream Flow Service Group, U.S. Fish and Wildlife Service. Fort Collins, Colorado.
- Bovee, K. D, B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream habitat analysis using the instream flow incremental methodology. U.S. Geological Survey, Biological Resources Division Information and Technology Report USGS/BRD-1998-0004. viii + 131 pp.
- Carlander, K.D. 1969. *Handbook of freshwater fishery biology*, Volume 1. Iowa State University Press, Ames, Iowa.
- Conder, A. L., and T. C. Annear. 1987. Test of weighted usable area estimates derived from a PHABSIM model for instream flow studies on trout streams. *North American Journal of Fisheries Management* 7:339–350.
- De Rito, Jr. J. N. 2005. Assessment of reproductive isolation between Yellowstone cutthroat trout and rainbow trout in the Yellowstone River, Montana. Master's thesis. Montana State University, Bozeman, Montana.
- De Staso, J., III and F. J. Rahel. 1994. Influence of water temperature on interactions between juvenile Colorado River cutthroat trout and brook trout in a laboratory stream. *Transactions of the American Fisheries Society* 123:289-297.
- Dey, P. D., and T. C. Annear. 2002. Instream flow studies on Francs Fork, a Greybull River tributary. Administrative Report. Wyoming Game and Fish Department, Fish Division, Cheyenne, Wyoming.

- Dey, P. D., and T. C. Annear. 2003. Instream Flow studies on Pickett Creek, a Greybull River tributary. Administrative Report. Wyoming Game and Fish Department, Fish Division, Cheyenne, Wyoming.
- Dey, P. D., and T. C. Annear. 2006. Trout Creek, tributary to North Fork Shoshone River, instream flow studies. Administrative Report. Wyoming Game and Fish Department, Fish Division, Cheyenne, Wyoming.
- Dwyer, W. P., and R. H. Kramer. 1975. The influence of temperature on scope for activity in cutthroat trout, *Salmo clarki*. Transactions of the American Fisheries Society 3:552-554.
- Dunham, J. B., M. M. Peacock, B. E. Rieman, R. E. Schroeter, and G. L. Vinyard. 1999. Geographic variability in the distribution of stream-living Lahontan cutthroat trout. Transactions of the American Fisheries Society 128:875-889.
- Heede, B. H. 1992. Stream dynamics: An overview for land managers. Fort Collins: U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station (General Technical Report RM-72).
- Hubert, W. A., C. A. Pru, T. A. Wesche, and T. Bray. 1997. Evaluation of flow duration analysis to establish winter instream flow standards for Wyoming trout streams. Final Report WWRC-97-03. Wyoming Water Resources Center, Laramie, Wyoming.
- Isaak, D.J. and W.A. Hubert. 2004. Nonlinear response of trout abundance to summer stream temperatures across a thermally diverse montane landscape. Transactions of the American Fisheries Society 133:1254-1259.
- Kent, R. 1984. Fisheries management investigations in the upper Shoshone River drainage 1978–1982. Administrative Report. Wyoming Game and Fish Department, Fish Division, Cheyenne, Wyoming.
- Kiefling, J. W. 1978. Studies on the ecology of the Snake River cutthroat trout. Fisheries Technical Bulletin No. 3, Wyoming Game and Fish Department, Cheyenne, Wyoming.
- Komura, S., and D. B. Simons. 1967. River-bed degradation below dams. J. Hydraulics Div. ASCE 93(4): 1-13.
- Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial processes in geomorphology. Freeman, San Francisco, CA, 522 pp.
- Lindstrom, J. W., and W. A. Hubert. 2004. Ice processes affect habitat use and movements of adult cutthroat trout and brook trout in a Wyoming foothills stream. North American Journal of Fisheries Management 24:1341–1352.
- Locke, A. and A. Paul. 2011. A desk-top method for establishing environmental flows in Alberta rivers and streams. Alberta Environment and Alberta Sustainable Resource Development, 94 pp.

- May, B., S. E. Albeke, and T. Horton. 2007. Range-wide status assessment for Yellowstone cutthroat trout (*Oncorhynchus clarkii bouveri*): 2006. Yellowstone Cutthroat Trout Conservation Team Report. Montana Fish, Wildlife & Parks, Helena, Montana. 410 pp.
- Meyer, K. A., D. J. Schill, F. S. Elle, and J. A. Lamansky, Jr. 2003. Reproductive demographics and factors that influence length at sexual maturity of Yellowstone cutthroat trout in Idaho streams. *Transactions of the American Fisheries Society* 132:183–195.
- Milhous, R. T., D. L. Wegner, and T. Waddle. 1984. User's guide to the physical habitat simulation system. Instream Flow Paper 11, FWS/OBS-81/43, U.S. Fish and Wildlife Service, Fort Collins, Colorado.
- Milhous, R. T., M. A. Updike, and D. M. Schneider. 1989. Physical habitat simulation system reference manual - version II. Instream Flow Information Paper No. 26. U.S. Fish and Wildlife Service, Biological Report 89(16).
- Nehring, R. 1979. Evaluation of instream flow methods and determination of water quantity needs for streams in the state of Colorado. Colorado Division of Wildlife, Fort Collins, Colorado.
- Nilsson, C., G. Grelsson, M. Johansson, and U. Sperens. 1989. Patterns of plant species richness along riverbanks. *Ecology* 70:77-84.
- Novinger, D. C. 2000. Reversals in competitive ability: do cutthroat trout have a thermal refuge from competition with brook trout? Doctoral dissertation, University of Wyoming, Laramie, Wyoming.
- Payne, T. R. 2003. The concept of weighted useable area as relative suitability index. In Lamb, B. L., D. Garcia de Jalon, C. Sabaton, Y. Souchon, N. Tamai, H. R. Robinette, T. J. Waddle, and A. Brinson, editors. 2003. Proceedings of the International IFIM User's Workshop. Colorado State University, Office of Conference Services, Fort Collins, Colorado.
- Robertson, M.S., and T. C. Annear. 2011. Water management unit plan and stream prioritization. Administrative Report. Wyoming Game and Fish Department, Fish Division, Cheyenne.
- Rosgen, D. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, Colorado.
- Thurow, R. F. and J. B. King. 1994. Attributes of Yellowstone cutthroat trout redds in a tributary of the Snake River, Idaho. *Transactions of the American Fisheries Society* 123:37–50.
- Varley, J. D. and R. E. Gresswell. 1988. Ecology, status, and management of the Yellowstone cutthroat trout. Pages 13–24 in R.E. Gresswell, editor. Status and management of interior stocks of cutthroat trout. American Fisheries Society, Symposium 4, Bethesda, MD.

- Ward, J. V. 1989. The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society* 8(1):2-8.
- Wyoming Game and Fish Department (WGFD). 2009. Strategic Habitat Plan. Administrative Report. Wyoming Game and Fish Department, Fish Division, Cheyenne.
- Wyoming Game and Fish Department (WGFD). 2010. State Wildlife Action Plan. Wyoming Game and Fish Department. Cheyenne, WY.
- Wyoming Water Resources Data System (WRDS). 2015. Map server. Available at: <http://www.wrds.uwyo.edu/sco/data/PRISM/PRISM.html>. Accessed on March 16, 2015.
- Wyoming Department of Environmental Quality (WYDEQ). 2013. Wyoming surface water classification list. Available at: <http://deq.wyoming.gov/wqd/surface-water-quality-standards/>. Wyoming Department of Environmental Quality, Cheyenne, Wyoming.

## ***Appendix A. Instream Flows in Wyoming***

### ***Legal and Institutional Background***

The instream flow law, W.S. 41-3-1001-1014, was passed in 1986 and establishes that “unappropriated water flowing in any stream or drainage in Wyoming may be appropriated for instream flows to maintain or improve existing fisheries and declared a beneficial use...” The statute directs that the Wyoming Game and Fish Commission (WGFC) is responsible for determining stream flows that will “maintain or improve” important fisheries. The Wyoming Game and Fish Department (WGFD) fulfills this function under the general policy oversight of the WGFC. The WGFD conducts biological studies to determine the quantity of flow needed to maintain or improve fisheries. The Wyoming Water Development Office conducts a feasibility study to determine the availability of flow to meet the recommendations and submits the instream flow water right applications. If approved by the State Engineer, instream flow water rights are held by the Wyoming Water Development Office on behalf of the state. The priority date for the instream flow water right is the day the application is received by the State Engineer. As with all other water rights in Wyoming, the doctrine of prior appropriation applies and instream flow water rights are junior to all existing water rights in the stream. Permitted instream flow water rights will not affect the lawful use of water for senior rights.

### ***Biological Studies***

Studies designed to evaluate instream flow needs for fisheries in Wyoming are initiated by the WGFC. Important stream fisheries are identified throughout the state and studies are conducted in each stream to determine how much flow is needed to maintain or improve these fisheries. A comprehensive instream flow study is designed to consider all five riverine ecosystem components (hydrology, biology, geomorphology, water quality and connectivity) and all aspects of each component (e.g., long-term habitat processes; Annear et al. 2004); however, the instream flow statute has been interpreted by the Wyoming State Engineer’s Office as applying only to direct fishery response to changes in flow. Other important components that influence stream conditions and fish populations, such as geomorphology, water quality and connectivity, are not considered when making instream flow recommendations (though information is provided in biological study reports, where available).

From a natural resource perspective, a fishery includes the habitat and associated natural processes that are required to support fish populations. The primary components that comprise physical habitat include, but are not limited to, the stream channel, riparian zone and floodplain as well as the processes of sediment flux and riparian vegetation development that sustain those habitats (Annear et al. 2004). To maintain the existing dynamic character of an entire fishery, instream flow regimes must maintain the stream channel and its functional linkages to the riparian corridor and floodplain to perpetuate habitat structure and ecological function. Until the interpretation of state water law changes to include a full range of flows of a dynamic fishery, channel maintenance flow recommendations are not included on instream flow applications, but are presented in an appendix of the biological studies report.

### ***Guiding Principles for Instream Flow Recommendations***

The analyses and interpretation of data collected for instream flow studies include consideration of the important components of an aquatic ecosystem and their relationship to stream flow. Stream ecosystems are complex, and maintaining this complexity requires an

appropriate flow regime. The recommendations of the Instream Flow Council (IFC), an organization of state and provincial fishery and wildlife management agencies, provide comprehensive guidance on conducting instream flow studies. The approach described by the IFC includes consideration of three policy components (legal, institutional, and public involvement) and five riverine components (hydrology, geomorphology, biology, water quality and connectivity; Annear et al. 2004). By using the eight components described by the IFC as a guide, WGFD strives to develop instream flow recommendations that work within Wyoming's legal and institutional environment to maintain or improve important aquatic resources for public benefit while also employing a generally recognized flow quantification protocol.

### ***Public Participation***

The general public has several opportunities to be involved in the process of identifying instream flow segments or commenting on instream flow applications. Individuals or groups can inform WGFD of their interest in protecting the fisheries in specific streams or stream segments with instream flow filings. In addition, planning and selection of future instream flow study sites are detailed in the WGFD Water Management Unit's work plan (Robertson and Annear 2011).

The public is also able to comment on instream flow water rights that have been filed with the State Engineer through public hearings, which are required by statute and conducted by the State Engineer's Office for each proposed instream flow water right. The State Engineer uses these public hearings to gather information for consideration before issuing a decision on the instream flow water right application.

Instream flow segments are nearly always located on public land; however, landowners adjacent to a proposed segment have the opportunity to request that the state extend an instream flow segment on the portion or portions of those streams crossing their property. Any such requests must be made in writing to the department. Instream flow segments are not located on private lands without such a request.

### ***Literature Cited***

- Annear, T., I. Chisholm, H. Beecher, A. Locke, and 12 other authors. 2004. *Instream Flows for Riverine Resource Stewardship. Revised edition.* Instream Flow Council, Cheyenne, Wyoming.
- Locke, A., C. Stalnaker, S. Zellmer, K. Williams, H. Beecher, T. Richards, C. Robertson, A. Wald, A. Paul, and T. Annear. 2008. *Integrated approaches to riverine resource management: Case studies, science, law, people, and policy.* Instream Flow Council, Cheyenne, Wyoming. 430 pp.
- Robertson, M.S., and T. C. Annear. 2011. *Water management unit plan and stream prioritization.* Administrative Report. Wyoming Game and Fish Department, Fish Division, Cheyenne.

## **Appendix B. Channel Maintenance Flows**

### ***Background***

Maintaining a dynamic flow regime within the natural range of variability and including occasional high flows, is important in streams for maintaining diverse in-channel habitat for fisheries and riparian and floodplain vegetation (Kuhnle et al. 1999). A managed flow regime should mimic natural dynamic hydrographs within and between years (Gordon 1995, Trush and McBain 2000, Schmidt and Potyondy 2004) and include these higher flows that maintain the channel form and habitat conditions for fish over the long term (decades). High flows are needed in some years to scour the stream channel, prevent encroachment of stream banks, and deposit sediments on the floodplain to maintain a dynamic alternate bar morphology and a riparian community with diverse successional states (Carling 1995, Annear et al. 2004, Locke et al. 2008). Low flow years allow establishment of riparian seedlings on bars deposited in immediately preceding wet years (Trush and McBain 2000). Any time water is extracted from a stream the natural dynamic patterns change; larger quantities of extraction have a greater impact on habitat conditions and the organisms associated with those habitats. If naturally-occurring high flows were substantially reduced on a regular basis, it would have negative impacts on habitat, riparian assemblage of plants and animals, and ultimately the resident fishery (Stromberg and Patten 1990, Rood et al. 1995, Mahoney and Rood 1998).

The term “channel maintenance flows” refers to flows that maintain existing channel morphology, riparian vegetation and floodplain function (Schmidt and Potyondy 2004). The basis and approach used for defining channel maintenance flows applies to snowmelt-dominated gravel and cobble-bed (alluvial) streams and “identifies the minimum essential regime of streamflows necessary for the channel and its floodplain to remain fully functioning with respect to sediment and flow conveyance.” These are streams whose beds are dominated by loose material with median sizes larger than 0.08 in. and with a pavement or armor layer of coarser materials overlaying the channel bed. In these streams, bedload transport processes determine the size and shape of the channel and the character of habitat for aquatic organisms (Andrews 1984, Hill et al. 1991, Leopold 1994).

A flow regime that includes sufficient flow for channel maintenance results in stream channels that are in approximate sediment equilibrium, where sediment export equals sediment import on average over a period of years (Leopold 1994, Carling 1995, Schmidt and Potyondy 2004). Thus, stream channel characteristics over space and time are a function of sediment input and flow (Schmidt and Potyondy 2004). When sediment-moving flows are removed or reduced over a period of years, some gravel-bed channels respond with reductions in width and depth, rate of lateral migration, stream-bed elevation, stream side vegetation, water-carrying capacity, and changes in bed material composition.

Channel maintenance flows must be sufficient to move the entire volume and all sizes of material supplied to the channel from the watershed over a long-term period (Carling 1995, Schmidt and Potyondy 2004). A range of flows, under the dynamic hydrograph paradigm, provides this function. Infrequent high flows move large bed elements while the majority of the total volume of material is moved by more frequent but lower flows (Wolman and Miller 1960, Leopold 1994). In streams with a wide range of sediment sizes on the channel boundary, a range of flows may best represent the dominant discharge because different flow velocities are needed to mobilize different sizes of bed load and sediment. Kuhnle et al. (1999) noted “A system designed with one steady flow to transport the supplied mass of sediment would in all likelihood

become unstable as the channel aggraded and could no longer convey the sediment and water supplied to it.”

### **Bedload Transport**

A bedload transport model (Figure B-1) shows the total amount of bedload sediment transported over time (during which a full range of stream discharge [ $Q$ ] values occur). Smaller discharges, such as the substrate mobilization flow ( $Q_m$ ) occur more frequently, but not much sediment is moved during those times. The effective discharge ( $Q_e$ ) mobilizes the greatest volume of sediment and also begins to transport some of the larger sediment particles (gravels and small cobbles). The bankfull discharge ( $Q_{bf}$ ), in which flow begins to inundate the floodplain and which has a return interval of approximately 1.5 years on average, typically occurs near the  $Q_e$ . The discharge corresponding to the 25-year return interval ( $Q_{25}$ ) represents the upper limit of the required channel maintenance flow regime, since the full range of mobile sediment materials move at flows up to this value, but these higher flows are infrequent. The more frequent discharges that occur between the  $Q_m$  and the  $Q_e$  move primarily smaller-sized particles (sand and small gravel) and prevent filling in of pools and other reduction in habitat complexity. Since these particles are deposited into the stream from the surrounding watershed with greater frequency, it is important to maintain a flow regime that provides sufficient conveyance properties (high frequency of moderate discharges) to move these particles through the system. However, alluvial streams, particularly those at higher elevations, also receive significant contributions of larger-sized particles from the surrounding watershed and restrictions to the flow regime that prevent or reduce the occurrence of flows greater than  $Q_e$  (which are critical for moving these coarser materials) would result in gradual bedload accumulation of these larger particles. The net effect would be an alteration of existing channel forming processes and habitat (Bohn and King 2001). For this reason, flows up to the  $Q_{25}$  flow are required to maintain existing channel form and critical habitat features for local fish populations.

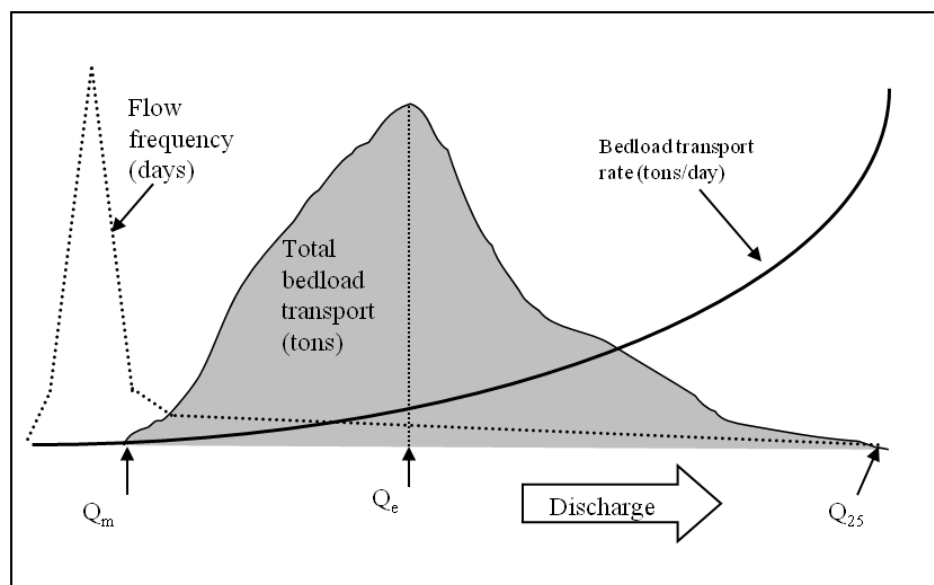


FIGURE B-1. Total bedload transport as a function of bedload transport rate and flow frequency (adapted from Schmidt and Potyondy 2004).

### ***Channel Maintenance Flows Model***

The model used to recommend flows to maintain the form and function of the stream channel is derived from bedload transport theory presented above. Based on these principles, the following channel maintenance flow model was developed by Dr. Luna Leopold and is used in this report to calculate the appropriate instream flows up to the  $Q_{25}$ :

$$Q \text{ Recommendation} = Q_f + \{(Q_s - Q_f) * [(Q_s - Q_m) / (Q_{bf} - Q_m)]^{0.1}\}$$

Where:  $Q_s$  = actual stream flow  
 $Q_f$  = fish flow (required to maintain fish spawning habitat)  
 $Q_m$  = sediment mobilization flow =  $0.8 * Q_{bf}$   
 $Q_{bf}$  = bankfull flow

The Leopold model calculations could be used to yield a continuous range of instream flow recommendations at flows between the  $Q_m$  and  $Q_{bf}$  for each cubic foot per second increase in discharge. However, this manner of flow regulation is complex and could prove burdensome to water managers. To facilitate flow administration while still ensuring sufficient flows for channel maintenance, we modified this aspect of the approach to recommend a single instream flow for each of four quartiles between the  $Q_m$  and  $Q_{bf}$ .

Channel maintenance flow recommendations developed with the Leopold model require that only a portion of the flow remain instream for maintenance efforts. When total discharge is less than  $Q_m$ , only fish flows are necessary; discharge between the fish habitat flows recommended in the main body of this report and  $Q_m$  is available for other uses (Figure B-2). Similarly, all discharge greater than the  $Q_{25}$  flow is less critical for channel maintenance purposes and available for other uses (these higher flows do allow a connection to the floodplain and it is valuable for infrequent inundation of riparian habitat to occur, but not for the physical maintenance of the stream channel). Between the  $Q_m$  and  $Q_{bf}$ , the model is used to determine what proportion of flow should remain in channel for maintenance activities. For those relatively infrequent flows that occur in the range between  $Q_{bf}$  and the  $Q_{25}$ , all flow is recommended to remain in the channel for these critical channel maintenance purposes.

Using this “dynamic hydrograph” approach, the volume of water required for channel maintenance is variable from year to year. During low-flow years, less water is recommended for channel maintenance because flows may not reach the defined channel maintenance level. In those years, most water in excess of fish habitat flows is available for other uses. The majority of flow for channel maintenance occurs during wet years. One benefit of this dynamic hydrograph approach is that the recommended flow is needed only when it is available in the channel and does not assert a claim for water that is not there as often happens with a threshold approach.

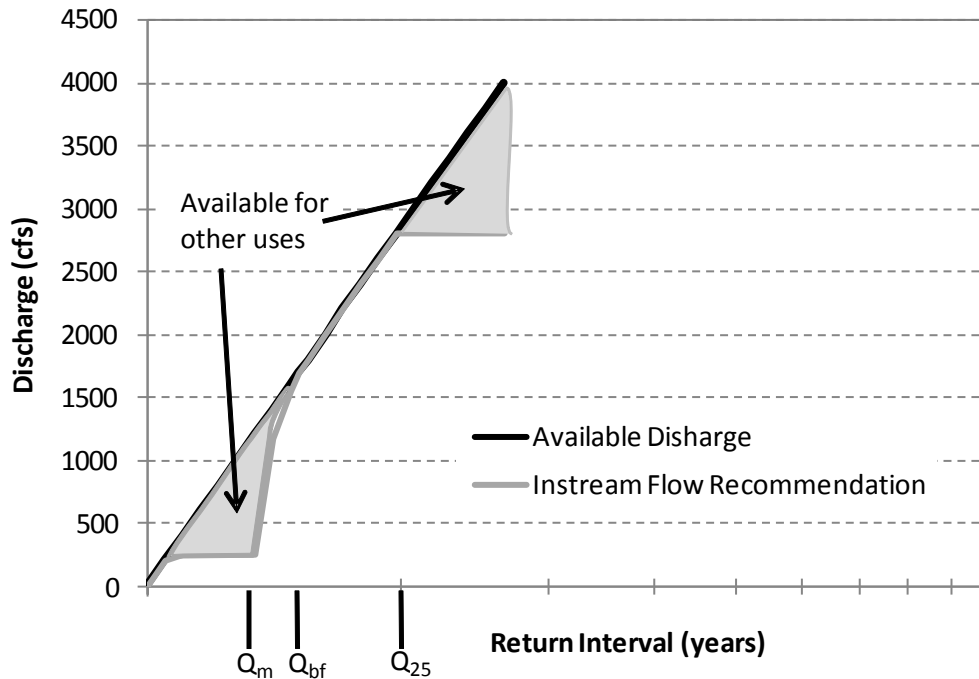


FIGURE B-2. Generalized dynamic hydrograph indicating recommended instream flow for fishery maintenance.  $Q_m$  is substrate mobilization flow,  $Q_{bf}$  is bankfull flow, and  $Q_{25}$  is the discharge with a 25-year return interval.

This channel maintenance flow model is the same as the one presented in Gordon (1995) and the Clark's Fork instream flow water right (C112.0F) filed by the U.S. Forest Service with the Wyoming State Engineer, with one exception. The model presented in those documents used the average annual flow to represent  $Q_m$ . Subsequent work by Schmidt and Potyondy (2004) identified  $Q_m$  as occurring at a discharge of 0.8 times  $Q_{bf}$ . Initial particle transport begins at flows somewhat greater than average annual flows but lower than  $Q_{bf}$  (Schmidt and Potyondy 2004). Ryan (1996) and Emmett (1975) found the flows that generally initiated transport were between 0.3 and 0.5 of  $Q_{bf}$ . Movement of coarser particles begins at flows of about 0.5 to 0.8 of  $Q_{bf}$  (Leopold 1994, Carling 1995). Schmidt and Potyondy (2004) discuss phases of bedload movement and suggest that a flow trigger of 0.8 of the  $Q_{bf}$  "provides a good first approximation for general application" in defining flows needed to maintain channels.

### ***Muddy Creek***

Like all properly functioning rivers, Muddy Creek has a hydraulically connected watershed, floodplain, riparian zone, and stream channel. Bankfull and overbank flow are essential hydrologic characteristics for maintaining the habitat in and along these river segments in their existing, dynamic forms. These high flows flush sediments from the gravels and maintain channel form (i.e., depth, width, and pool and riffle configuration) by periodically scouring encroaching vegetation. Overbank flow maintains recruitment of riparian vegetation, encourages lateral movement of the channel, and recharges ground water tables. Instream flows

that maintain the connectivity of these processes over time and space are needed to maintain the existing fishery (Annear et al. 2004).

The Leopold model was used to develop channel maintenance recommendations for the Muddy Creek instream flow segment (Table B-1). The fish flow used in the analysis was the spring spawning flow (29 cfs). For naturally available flow levels less than the spawning flow, the channel maintenance instream flow recommendation is equal to natural flow. The spawning flow level is substantially less than  $Q_m$  (94 cfs). For the flow range between the spawning flow and  $Q_m$ , the channel maintenance flow recommendation is equal to the spawning flow (Table B-1). When naturally available flows range from  $Q_m$  to  $Q_{bf}$  (118 cfs), the Leopold formula is applied and results in incrementally greater amounts of water applied toward instream flow (Table B-1). At flows between  $Q_{bf}$  and  $Q_{25}$  (238 cfs), all stream flow is retained in the channel to perform maintenance functions. At flows greater than  $Q_{25}$ , only the  $Q_{25}$  flow is recommended for channel maintenance (Figure B-3).

TABLE B-1. Channel maintenance instream flow recommendations (May 1–Jul 15) to maintain existing channel forming processes and long-term aquatic habitat characteristics in the Muddy Creek instream flow segment.

Flow Description	Available Flow (cfs)	Recommended Flow (cfs)
<Spawning Flow	<29	All available flow
Spawning Flow to $Q_m$	29-94	29
$Q_m$ to $Q_{bf}$ – Quartile 1	95-100	80
$Q_m$ to $Q_{bf}$ – Quartile 2	101-106	94
$Q_m$ to $Q_{bf}$ – Quartile 3	107-112	103
$Q_m$ to $Q_{bf}$ – Quartile 4	113-118	111
$Q_{bf}$ to $Q_{25}$	118-238	All available flow
> $Q_{25}$	$\geq 238$	238

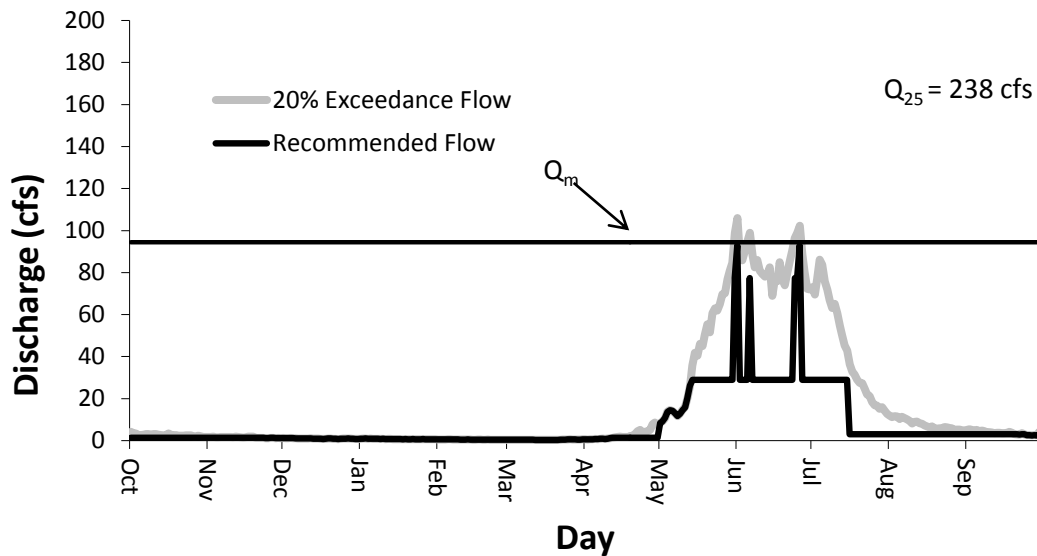


FIGURE B-3. Channel maintenance flow recommendations and hydrographs for the Muddy Creek instream flow segment if the flow were at the 20% exceedance flow all year.

Implementing these flow recommendations would have to include moderating the abrupt changes that occur at threshold flows with a ramping scheme that includes more gradual changes akin to a natural hydrograph. Such sharp flow increases and decreases evident in Figure B-3 would cause habitat loss through excessive scour and potential trout mortality due to stranding. In addition, spawning redds may be disturbed and fish recruitment negatively impacted without an appropriate ramping rate. The Index of Hydrologic Alteration (IHA; Richter et al. 1996) or other hydrologic summary models could provide a valuable reference to find suitable rates of change. Daily increases and decreases during runoff measured at the reference gage could serve as a guide for developing such ramping rate recommendations using the IHA.

## Literature Cited

- Annear, T., I. Chisholm, H. Beecher, A. Locke, and 12 other authors. 2004. Instream Flows for Riverine Resource Stewardship. *Revised edition*. Instream Flow Council, Cheyenne, Wyoming.
- Andrews, E. D. 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. *Geological Society of America Bulletin* 95:371–378.
- Bohn, C. C., and J. G. King. 2001. Stream channel responses to streamflow diversion on small streams in Idaho. *Stream Notes*. Stream Systems Technology Center, U.S. Forest Service, Fort Collins, Colorado. pp 6–7.
- Carling, P. 1995. Implications of sediment transport for instream flow modeling of aquatic habitat. In D. Harper and A. Ferguson, editors. *The Ecological Basis for River Management*. John Wiley & Sons, Chichester, England. pp17–32.

- Emmett, W. W. 1975. The channels and waters of the upper Salmon River area, Idaho. U.S. Geological Survey, Professional Paper 870-A. 116 pp.
- Gordon, N. 1995. Summary of technical testimony in the Colorado Water Division 1 Trial. USDA Forest Service, General Technical Report RM-GTR-270. 140 pp.
- Hill, M. T., W. S. Platts, and R. L. Beschta. 1991. Ecological and geo-morphological concepts for instream and out-of-channel flow requirements. *Rivers*, 2(3): 198–210.
- Kuhnle, R. A., A. Simon, and R. L. Bingner. 1999. Dominant discharge of the incised channels of Goodwin Creek. Published in the Proceedings 1999 Water Resources Conference, American Society of Civil Engineers. Seattle, Washington.
- Leopold, L. B. 1994. *A View of the River*. Harvard University Press, Cambridge, Massachusetts, 298 pp.
- Mahoney, J. M., and S. B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment: An integrative model. *Wetlands* 18(4): 634–645.
- Richter, B. D., J. V. Baumgartner, J. Powell, and D. P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10:1163–1174.
- Rood, S. B., J. M. Mahoney, D. E. Reid, and L. Zilm. 1995. Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. *Canadian Journal of Botany* 73:1250–1260.
- Ryan, S. E. 1996. Bedload transport patterns in coarse-grained channels under varying conditions of flow. *In* Proceedings of the 6<sup>th</sup> Inter-agency sedimentation conference, Las Vegas, Nevada, March 10–14. p VI-22 to VI-27b.
- Schmidt, L. D., and J. P. Potyondy. 2004. Quantifying channel maintenance instream flows: an approach for gravel-bed streams in the Western United States. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-128.
- Stromberg, J. C., and D. C. Patten. 1990. Riparian vegetation instream flow requirements: A case study from a diverted stream in the eastern Sierra Nevada, California, USA. *Environmental Management* 14(2): 185–194.
- Trush B., and S. McBain. 2000. Alluvial river ecosystem attributes. *Stream Notes*. January 2000. Stream systems technology Center, USDA Forest Service. pp 1–3.
- Wolman M. G., and J. P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* 68:54–74.

## ***Appendix C. Hydrology Estimates for the Ungaged Study Segment***

There are multiple methods for generating daily discharge estimates in ungaged stream segments; the one chosen for these estimates is based on watershed characteristics that can primarily be calculated from maps and climatology data from the study area. These watershed characteristics models were developed using stream gage data both regionally and statewide. The results of these calculations and flow estimates for the study site are compared with field data collected during the instream flow study. These results could be paired with a field hydrologic study (e.g., following the study design of Lowham 2009) to generate comprehensive flow estimates that have a higher probability of accuracy than either method used alone. An excellent example of how multiple flow estimation methods can be combined into a single set of daily discharge estimates is described in Parrett and Cartier (1990).

### ***Reference gage selection***

To estimate flows in an ungaged stream using a watershed characteristics model, a reference stream gage is first selected to provide baseline discharge data. The qualities of a good reference gage are: 1) that it be located close to the study site (within the same eight-digit HUC drainage is preferred, where possible), 2) that it have at least 10 years of continuous records (it is not necessary that it be in current operation, but this is preferable), and 3) that be in a stream with similar watershed characteristics (mean elevation, drainage area, stream width, etc.). Due to the limited number of stream gages in Wyoming, this combination is difficult to find for many study sites. Once a reference gage is selected, the recorded flow estimates from that gage are adjusted to correct for differences between it and the ungaged study stream. After this correction factor is applied, the period of record at the reference gage can be used to estimate flows over the same period (including generating monthly and annual summary statistics) at the study site.

In the area near the Muddy study site, there are 2 active and 2 inactive USGS stream gaging sites that have more than 20 years of data and were considered as potential reference gages (Table C-1). One active USGS gage with 16 years for a period of record was also considered. There were no local stream gages found on the Wyoming State Engineer's website for real-time stream flow data (Wyoming State Engineer 2015). All USGS gages were within the same HUC6 watershed (100700). The active gage on the Lamar River and the inactive gage on the Clarks Fork River both drain large basins (660 and 446 sq. miles, respectively), both much larger than the 12 square mile drainage area of the Muddy Creek instream flow segment. The active gage in Rock Creek and the inactive gage in Sunlight Creek both have smaller drainage basins of 105 and 135 square miles, respectively, making these better candidates. However, the gage with the most similar drainage area size is Soda Butte Creek at 31 square miles; it has a shorter period of record than the others, but still has more than 10 years. The Soda Butte gage is also located at a similar elevation to the study site and also had the best correlation between daily discharge data in 2014 and temporary stream gage data collected in Muddy Creek during the study period (see below). Based on these observations, the reference gage chosen to estimate conditions at the Muddy Creek study site was the one on Soda Butte Creek (06187915).

TABLE C-1. Potential USGS reference gages.

Gage Name	Gage Number	Period of Record	Drainage Area	Elevation (ft)
Lamar River near Tower Ranger Station YNP	06188000	1923-2015	660	6,000
Rock Creek near Red Lodge MT	06209500	1932-2015	105	6,400
Clarks Fork River below Crandall Creek	06206000	1929-1957	446	6,160
Sunlight Creek near Painter, WY	06206500	1945-1971	135	6,700
Soda Butte Cr at Park Boundary at Silver Gate	06187915	1998-2015	31	7,340

### *Temporary Stream Gage Data*

A temporary stream gage station was established upstream of the Muddy Creek study site between July 10, 2014 and September 27, 2014. Discharge measurements collected during the study period were used with stage readings from the staff plate during the same day to establish a rating curve (Figure C-1). This rating curve was then used to estimate discharge from water level readings at the study site (Figure C-2) and then these data were compared to daily discharge values at the potential reference gages (Figures C-3, C-4). The discharge estimates at the study site had a higher correlation to discharge data from the Soda Butte Creek gage.

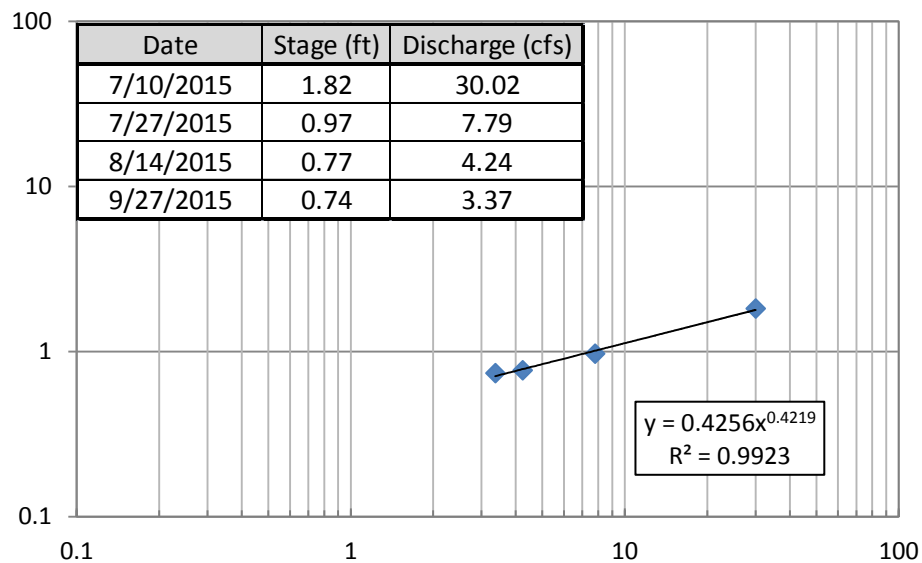


Figure C-1. Rating curve data for the temporary gage established at the Muddy Creek study site during 2014.

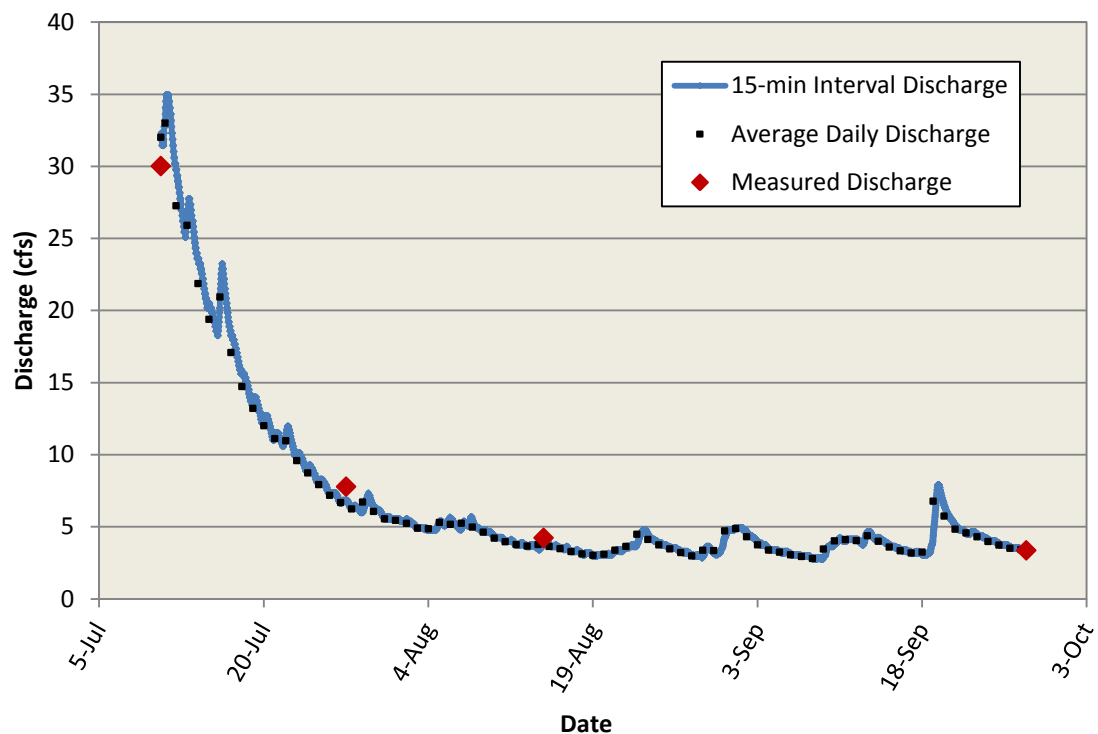


Figure C-2. Estimated hydrograph for Muddy Creek study site during 2014.

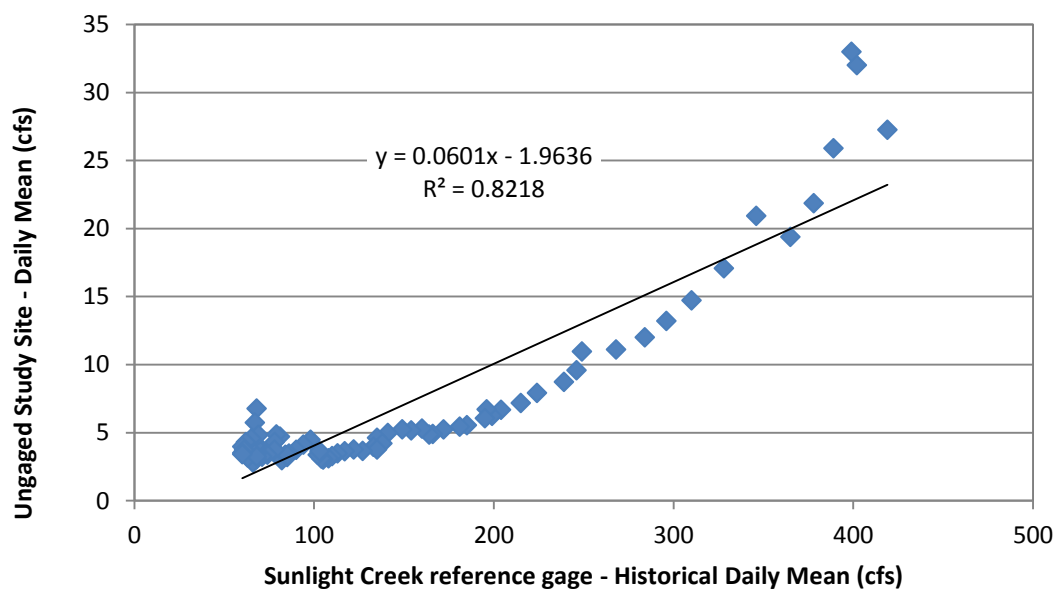


Figure C-3. Correlation between daily discharge estimates at the Muddy Creek study site in 2014 and the historical mean daily discharge for the same day-of-year at the Sunlight Creek stream gage.

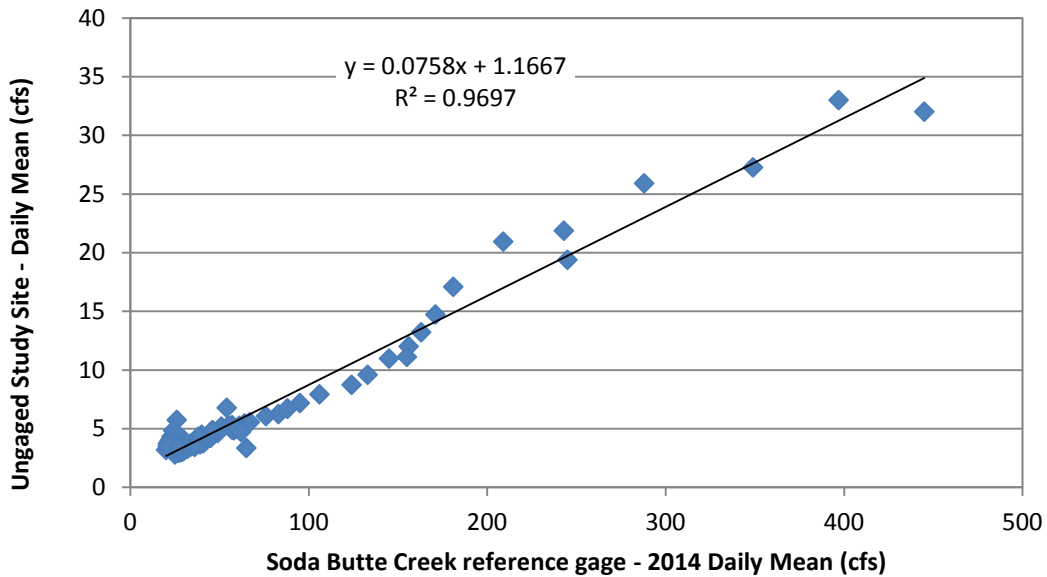


Figure C-4. Correlation between daily discharge estimates at the Muddy Creek study site in 2014 and the daily discharge for the same day at the Soda Butte Creek stream gage.

### ***Watershed Model Selection***

After selecting a reference gage, models using various watershed characteristics were evaluated to determine which watershed model is best suited to the conditions in the study area. There are several potential models that use variables that include mean elevation, drainage area, precipitation, stream length, and bankfull width to estimate mean annual flow ( $Q_{AA}$ ). In Wyoming streams, models for making these estimates are found in two primary sources, Lowham (1988) and Miselis et al. (1999). The Lowham (1988) models were based on streams found in mountainous areas statewide and the Miselis et al. (1999) models created separate models for each of eight specific mountain ranges. Each model is used to estimate  $Q_{AA}$  at the reference gage and the result is compared to the known  $Q_{AA}$  value. The watershed characteristics model that best predicts  $Q_{AA}$  at the reference gage is a good prospect for predicting  $Q_{AA}$  at the ungaged study site, though sometimes a detailed evaluation may provide support for an alternate model. Local discharge measurements or temporary stream gaging data at the study site provide additional data sources, when available, to help guide model selection.

The  $Q_{AA}$  for the Soda Butte reference gage (06187915) was 62 cfs for the 16 year period of record (1998-2015). Table C-2 shows how closely each of several possible models comes to estimating the actual  $Q_{AA}$  for this location. None of the watershed models predicted the  $Q_{AA}$  at the reference gage with good accuracy; the closest model was the Miselis model using drainage area for all mountainous areas in Wyoming which estimated flow at the gage should be 26.2 cfs.

TABLE C-2. Watershed models used to calculate  $Q_{AA}$  for the Soda Butte Creek reference gage.

Model Description	Model*	Upper Shell $Q_{AA}$ (cfs)
Miselis et al (1999): Mountainous for WY, Drainage Area	1.20976 DA <sup>0.894</sup>	26.2
Miselis et al (1999): Absaroka Mountains, Mean Elevation	4.47e40 BE <sup>-9.74</sup>	155
Miselis et al (1999): Absaroka Mountains, Drainage Area	0.43441 DA <sup>1.15</sup>	23
Miselis et al (1999): Absaroka Mountains, Precipitation	0.00014 P <sup>4.50</sup>	139
Miselis et al (1999): Absaroka Mountains, Stream Length	0.48040 SL <sup>1.80</sup>	13
Miselis et al (1999): Absaroka Mountains, Bankfull Width	0.01626 WBF <sup>2.14</sup>	121
Lowham (1988): Drainage area and Mean Elevation	0.0015DA <sup>1.01</sup> (Elev/1000) <sup>2.88</sup>	26.1
Lowham (1988): Drainage area and Precipitation	0.013DA <sup>0.93</sup> P <sup>1.43</sup>	25.6
Lowham (1988): Bankfull Width	0.087 W <sub>BF</sub> <sup>1.79</sup>	151
Historic gage records (16 years of record)		<b>62</b>

\*-Basin characteristics include: DA – drainage area (square miles); P – annual precipitation (inches); SL – stream length (miles); Elev – mean basin elevation (feet); Wbf – Bankfull channel width (feet).

### *Dimensionless analysis*

Once the watershed characteristics model was selected, a dimensionless analysis approach was used to develop estimates of daily flow, annual and monthly flow duration curves, and flood frequency for the proposed instream flow segment. The procedure uses the difference in the scale of the known  $Q_{AA}$  at the reference gage and the estimated  $Q_{AA}$  at the ungaged study sites to shift data from the reference gage up or down by the appropriate correction factor to estimates for the ungaged study site. The adjustment factor is a dimensionless value that uses average annual discharge ( $Q_{AA}$ ) for scaling according to the formula:

$$\frac{Q_1}{Q_{AA1}} = \frac{Q_2}{Q_{AA2}}$$

Where:

$Q_1$  = Daily discharge at the gage location

$Q_{AA1}$  = Average annual discharge at the gage location

$Q_2$  = Daily discharge at the ungaged study segment

$Q_{AA2}$  = Average annual discharge at the ungaged study segment

Daily discharge and  $Q_{AA}$  are known at the gage location. The watershed model provides the  $Q_{AA}$  estimate at the ungaged study site so the formula is rearranged to solve for  $Q_2$  (daily discharge at the ungaged location).

### *Flow Estimates for the Muddy Creek Study Site*

Using the watershed characteristics model of Miselis (1999) based on drainage area ( $1.20976 \cdot DA^{0.984}$ )  $Q_{AA}$  at the Muddy Creek study site was estimated to be 11.0 cfs. Daily flows

were estimated for the study site over the same period of record as the reference gage (1998-2015) and a graph of mean, 20 percent exceedance, and maximum daily discharge was prepared (Figure C-5). A flood frequency series (Table C-3) was calculated using the Log-Pearson Type III method and annual (Table C-4) and monthly (Table C-5) flow duration series were also calculated.

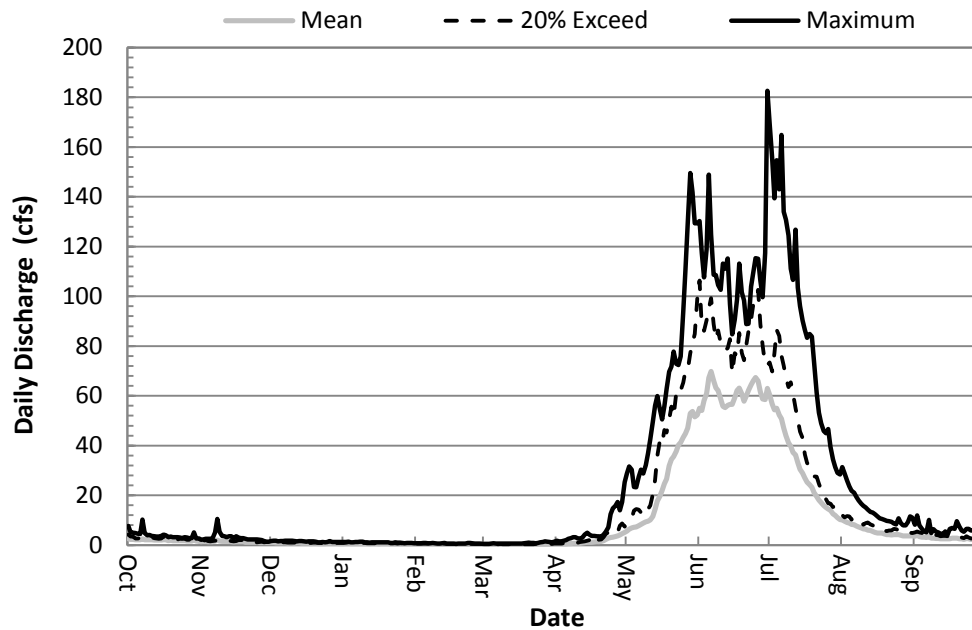


FIGURE C-5. Hydrograph showing the mean, 20 percent exceedance, and maximum daily discharge estimates for the Muddy Creek study site.

Table C-3. Flood frequency data for the Soda Butte Creek reference gage and estimated values at the Muddy Creek study site.

Return Period (years)	Soda Butte Creek (1998-2015)	Dimensionless (Q/QAA using gage data)	Muddy Creek
1.01	321	5.150	57
1.05	419	6.718	74
1.11	485	7.783	86
1.25	573	9.189	102
1.5	664	10.656	118
2	771	12.376	137
5	1018	16.330	180
10	1167	18.732	207
25	1343	21.556	238

Table C-4. Annual flow duration curve data for the Soda Butte Creek reference gage and estimated values at the Muddy Creek study site.

Duration Class (% Time Flow Equaled or Exceeded)	Annual Flow Soda Butte Creek (1998-2015)	Dimensionless (Q/QAA using gage data)	Predicted Annual Flow Muddy Creek
95	1.5	0.024	0.3
90	1.8	0.029	0.3
85	2.0	0.032	0.4
80	2.5	0.040	0.4
75	3.0	0.048	0.5
70	3.7	0.059	0.7
65	4.5	0.072	0.8
60	5.8	0.093	1.0
55	7.3	0.117	1.3
50	9.0	0.144	1.6
45	11	0.177	2.0
40	13	0.209	2.3
35	17	0.273	3.0
30	23	0.369	4.1
25	39	0.626	6.9
20	71	1.139	13
15	142	2.279	25
10	219	3.514	39
5	346	5.553	61

Table C-5. Monthly flow duration curve estimates for the Muddy Creek study site.

Duration Class (% time flow equaled or exceeded)	Streamflow (cfs)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
95	0.9	0.6	0.4	0.3	0.2	0.2	0.2	2.0	27	6.6	2.1	1.3
90	0.9	0.7	0.4	0.4	0.3	0.2	0.3	2.8	30	8.2	2.5	1.5
85	1.1	0.8	0.4	0.4	0.3	0.2	0.3	3.4	32	9.6	2.7	1.5
80	1.2	0.8	0.5	0.4	0.3	0.2	0.3	3.8	37	11	3.0	1.6
75	1.3	0.9	0.5	0.4	0.3	0.2	0.4	6.0	39	12	3.2	1.7
70	1.4	0.9	0.6	0.4	0.3	0.2	0.4	8.0	42	13	3.4	1.8
65	1.5	1.0	0.6	0.4	0.3	0.2	0.5	9.8	46	15	3.5	2.0
60	1.6	1.1	0.6	0.4	0.4	0.3	0.6	12	49	17	3.9	2.0
55	1.6	1.1	0.6	0.4	0.4	0.3	0.7	14	52	19	4.1	2.1
50	1.7	1.2	0.7	0.5	0.4	0.3	0.9	17	57	21	4.4	2.1
45	1.8	1.2	0.7	0.5	0.4	0.3	1.0	20	60	24	4.8	2.3
40	1.8	1.2	0.7	0.5	0.4	0.3	1.3	24	64	27	5.1	2.3
35	2.0	1.3	0.7	0.6	0.4	0.3	1.4	28	67	30	5.5	2.5
30	2.1	1.4	0.8	0.6	0.4	0.3	1.7	32	70	33	6.0	2.7
25	2.3	1.5	0.9	0.7	0.4	0.4	2.3	36	74	36	6.7	2.8
20	2.5	1.6	0.9	0.7	0.5	0.4	2.8	43	80	42	7.6	3.2
15	2.7	1.7	1.1	0.8	0.5	0.4	3.2	49	85	49	8.3	3.7
10	3.2	2.1	1.2	0.9	0.6	0.6	3.9	56	92	58	9.9	4.4
5	3.7	2.5	1.5	1.1	0.6	0.6	5.3	70	104	84	13	5.5

## Literature Cited

- Lowham, H. W. 1988. Streamflows in Wyoming. Water-Resources Investigations Report 88-4045, U.S. Geological Survey, Cheyenne, Wyoming.
- Lowham, H. W. 2009. Estimating streamflow from concurrent discharge measurements. Prepared for Wyoming Water Development Commission.
- Miselis, D. V., T. A. Wesche and H. W. Lowham. 1999. Development of hydrologic models for estimating streamflow characteristics of Wyoming's mountainous basins. Wyoming Water Resource Center Report, University of Wyoming, Laramie, Wyoming.
- Parrett, C. and K. D. Cartier. 1990. Methods for estimating monthly streamflow characteristics at ungaged sites in western Montana. U.S. Geological Survey Water-Supply Paper 2365.
- Wyoming State Engineer. 2015. Wyoming State Engineers Office WebPortal. Available at: <http://seoflow.wyo.gov/WDPortal/>. Accessed on March 16, 2015.